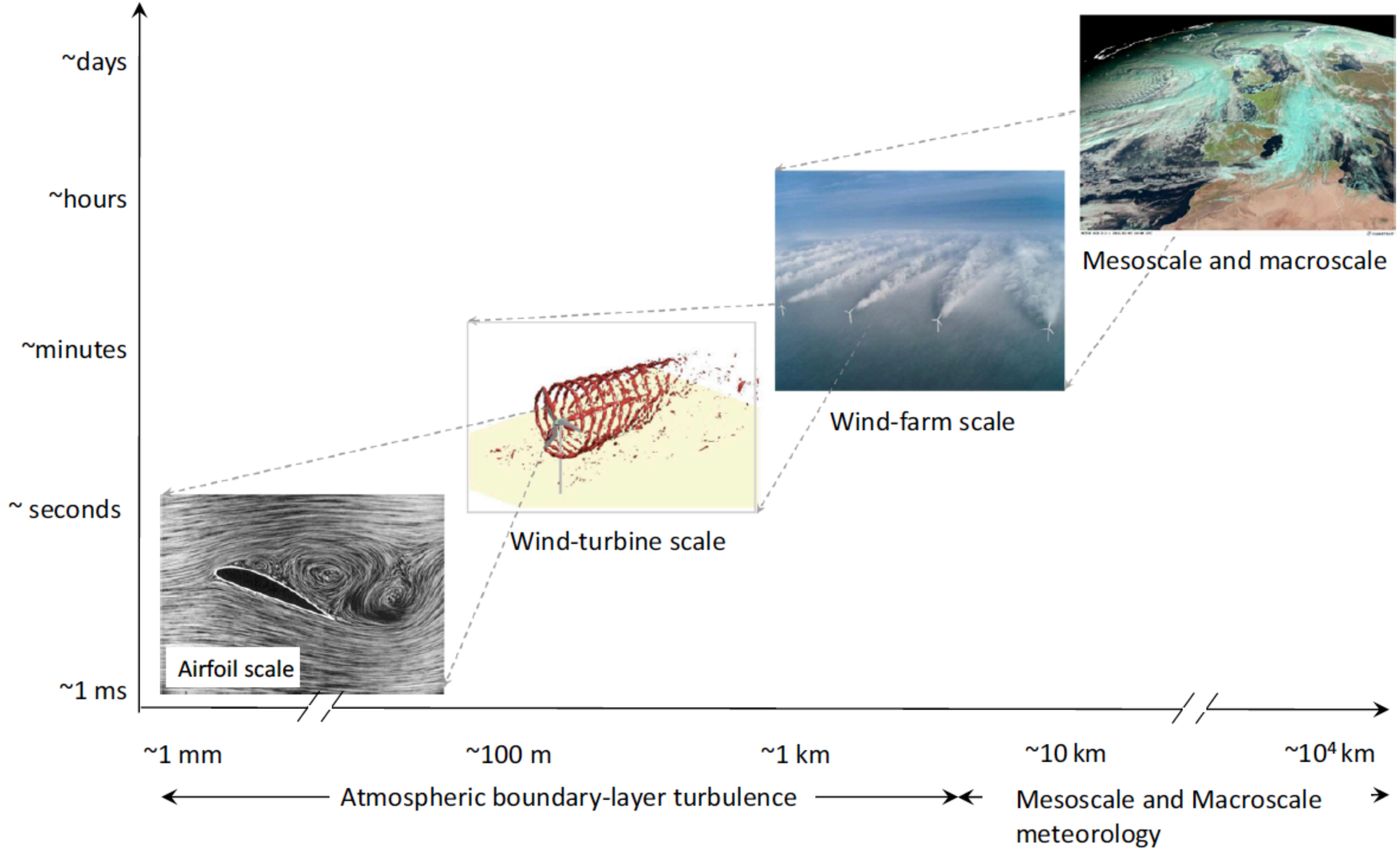
Advancing wind farm modeling through fluid physics and high-performance computing

Richard Stevens

Physics of Fluids

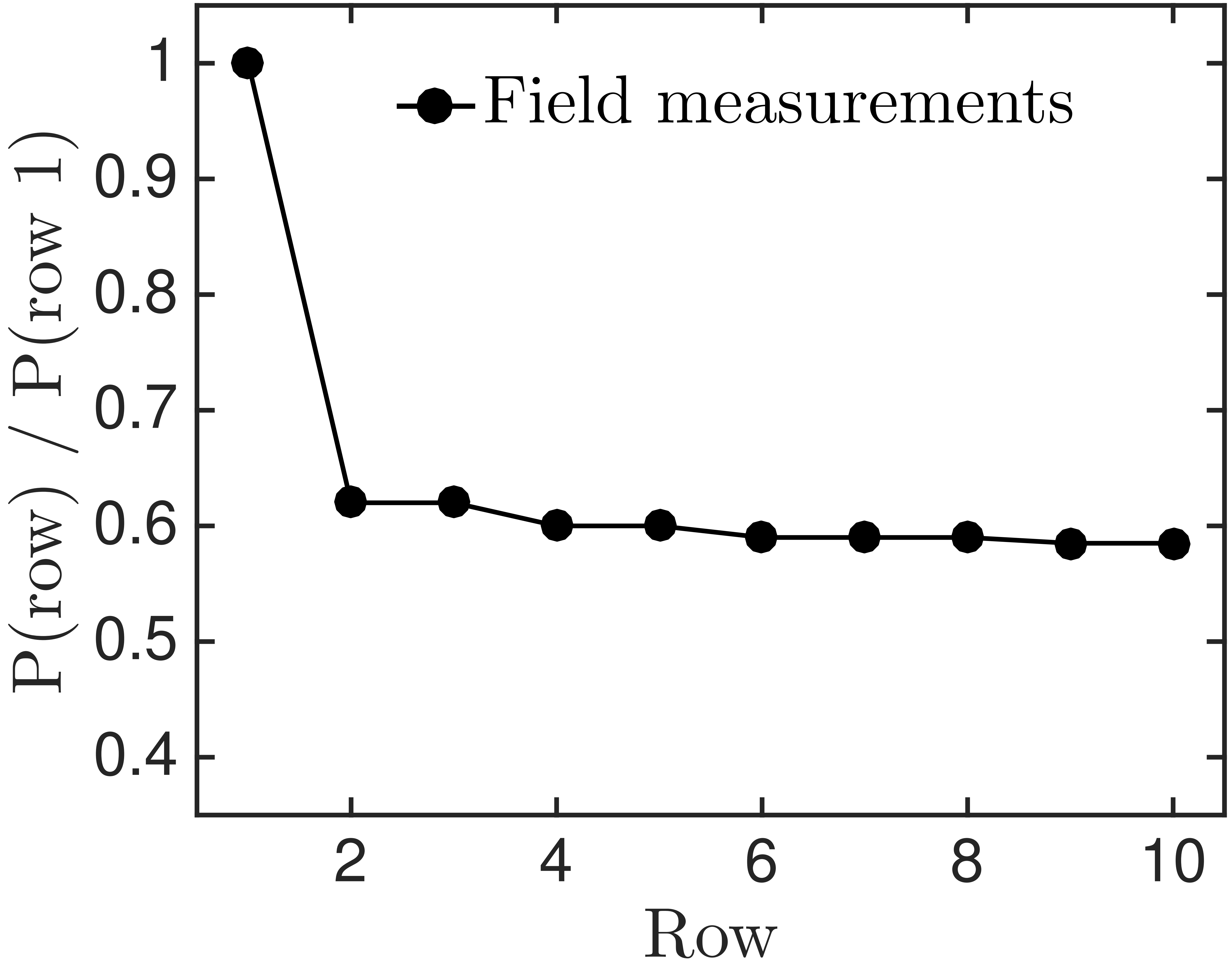
UNIVERSITY OF TWENTE.

Grand challenge: large range of length scales



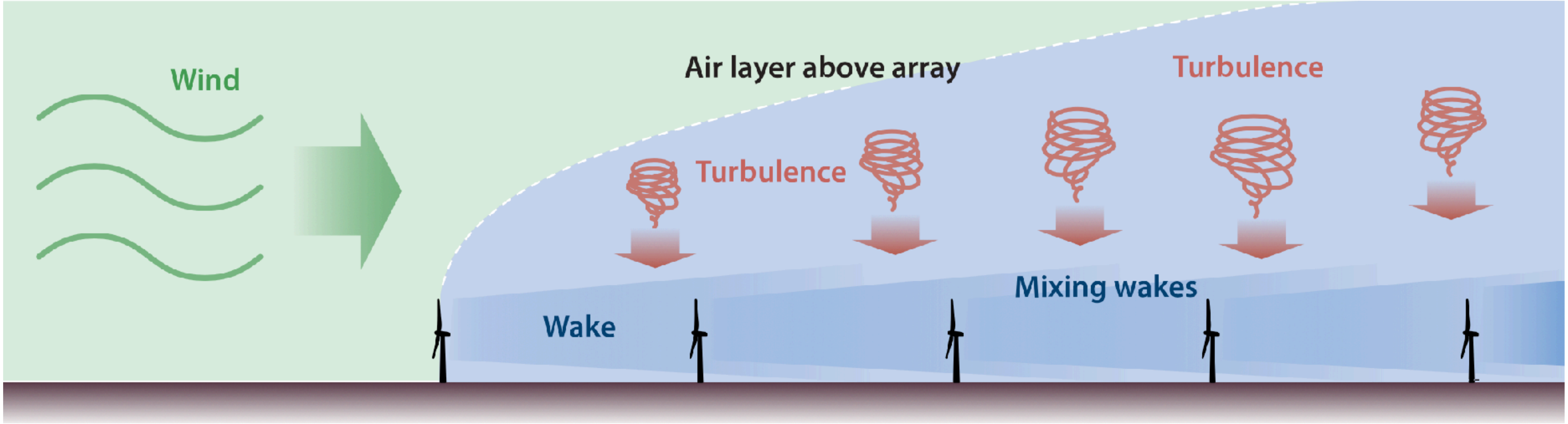
7 orders of magnitude!

Wake effects in wind farms



Barthelmie, et al, Final report for UpWind WP8, Risø-R-1765(EN), 012049 (2011)
Sørensen, Annu. Rev. Fluid Mech (2011), Emeis, DEWI Magazin 37, 52-55 (2010)

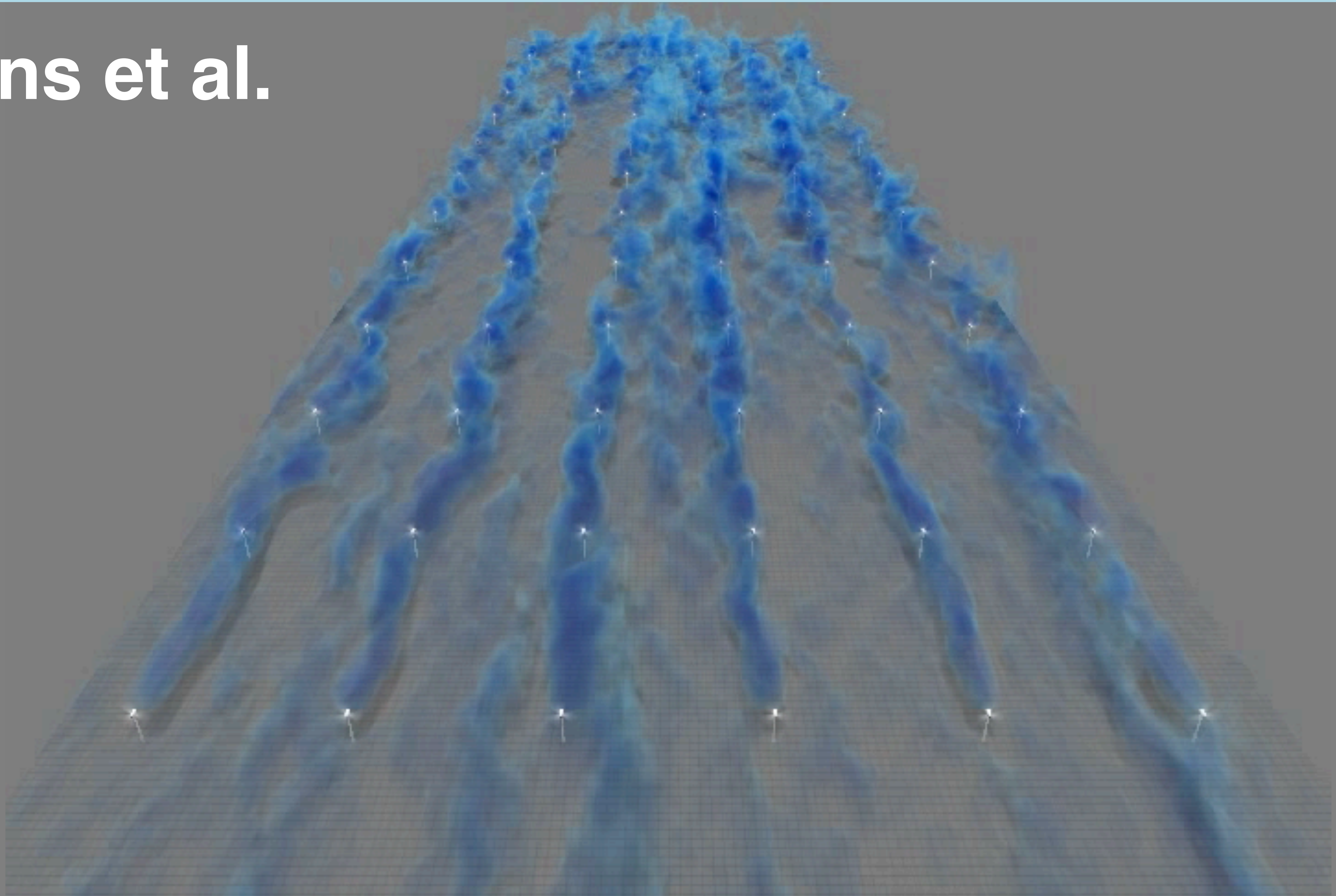
Fluid mechanics in wind farms



Wakes recover due to turbulent mixing

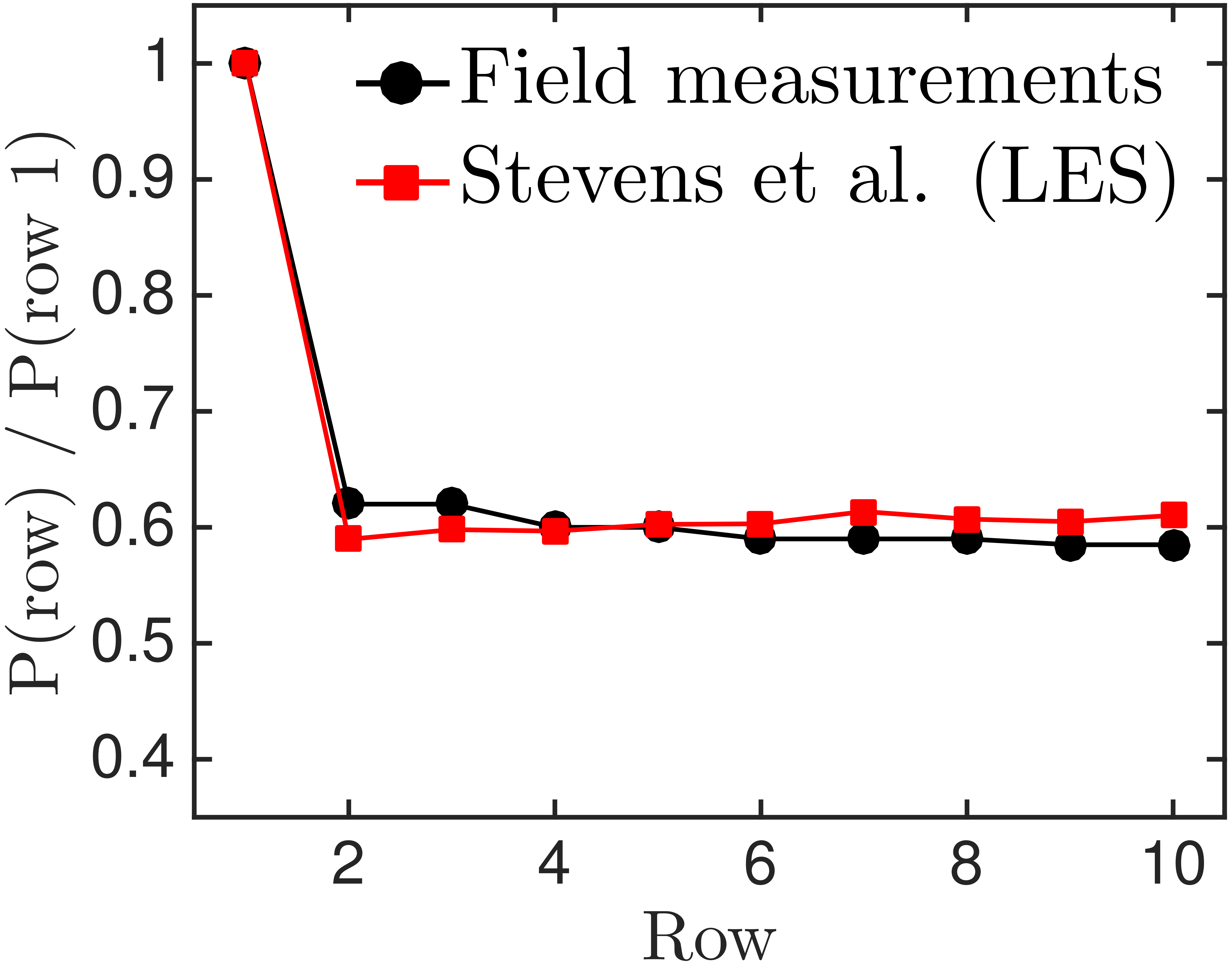
Stevens and Meneveau, Annu. Rev. Fluid Mech 49, 311-339 (2017)

Wind farm simulations



Stevens et al.

Wake effects in wind farms



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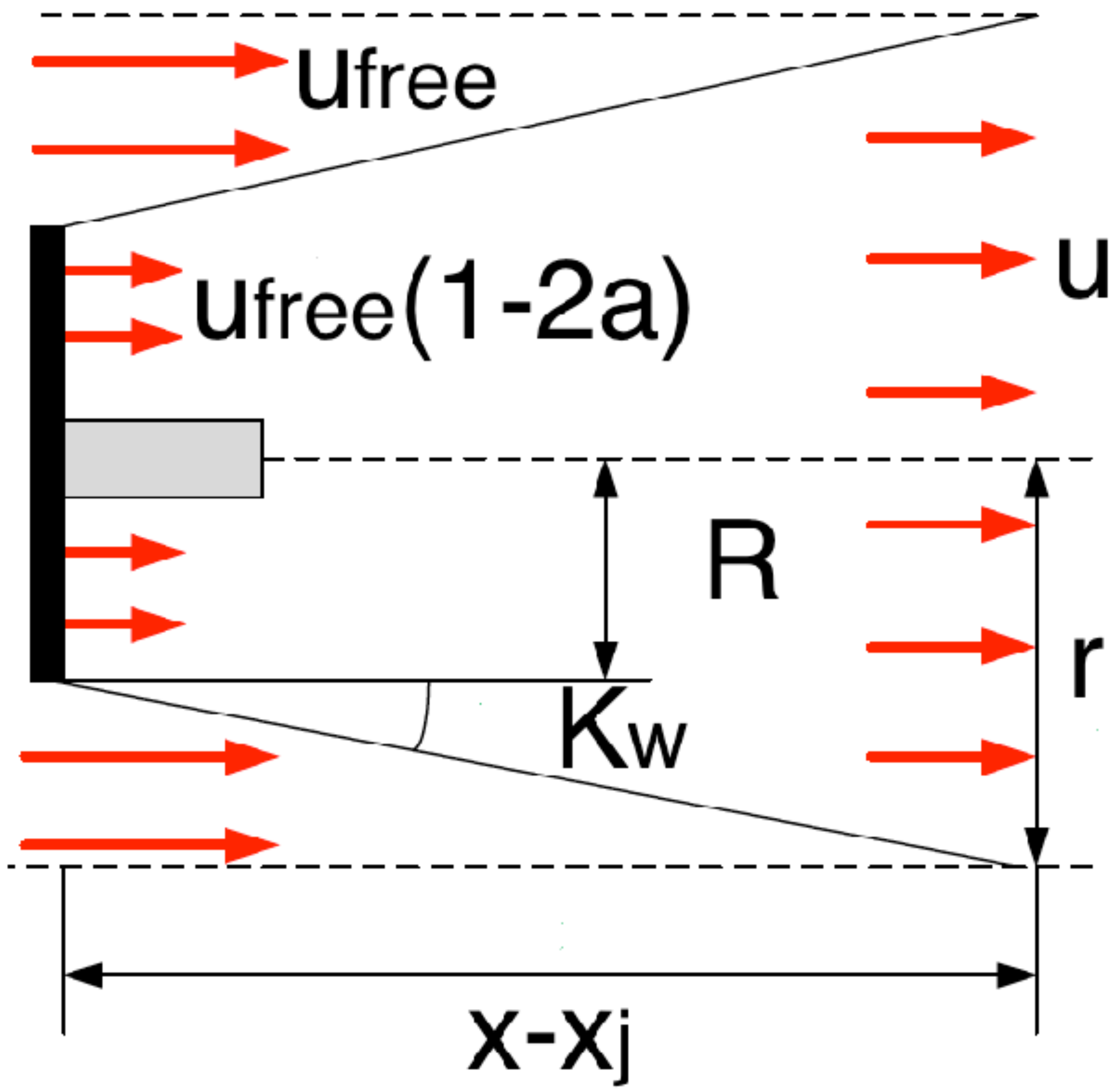
Wake models



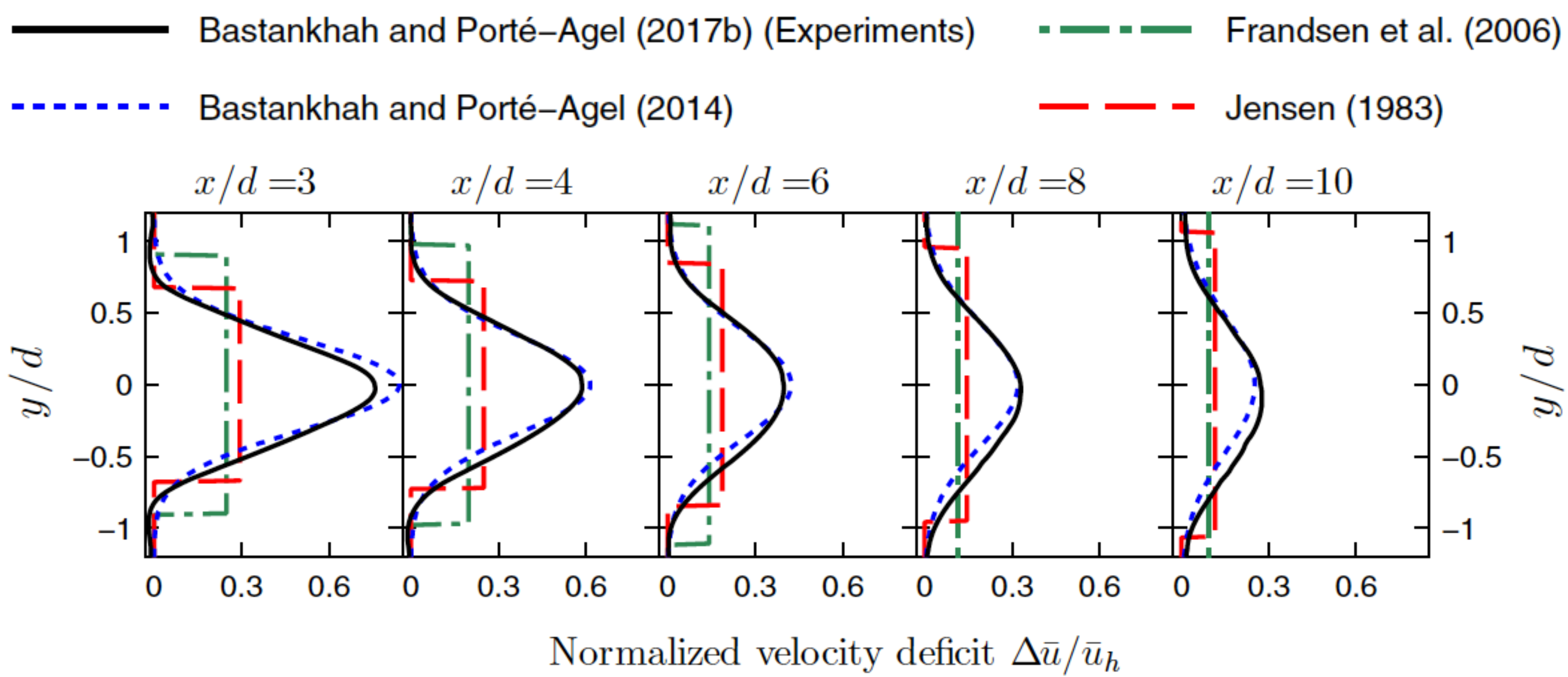
Momentum wake model gives velocity deficit

$$\delta u(\mathbf{x};j) = u_{\text{free}} - u(\mathbf{x};j) = \frac{2\,a\,u_{\text{free}}}{[1+k_w(x-x_j)/R]^2}$$

Lissaman (1979) / Jensen (1983)

Stevens and Meneveau, Annu. Rev. Fluid Mech 49, 311-339 (2017)
Porté-Agel, Bastankhah, Shamsoddin, Bound.-Layer Meteorol. 174, 1–59 (2020)

Wake models



Stevens and Meneveau, Annu. Rev. Fluid Mech 49, 311-339 (2017)
Porté-Agel, Bastankhah, Shamsoddin, Bound.-Layer Meteorol. 174, 1–59 (2020)

Modeling wake interactions

Superposition method	Definition
Lissaman (1979)	$u(\mathbf{X}) = u_\infty - \sum_{i=1}^{n} \Delta u_i(\mathbf{X})$, where $\Delta u_i(\mathbf{X}) = u_\infty - u_i(\mathbf{X})$
Katić et al. (1986)	$u(\mathbf{X}) = u_\infty - \sqrt{\sum_{i=1}^{n} \Delta u_i^2(\mathbf{X})}$, where $\Delta u_i(\mathbf{X}) = u_\infty - u_i(\mathbf{X})$
Voutsinas et al. (1990a)	$u(\mathbf{X}) = u_\infty - \sqrt{\sum_{i=1}^{n} \Delta u_i^2(\mathbf{X})}$, where $\Delta u_i(\mathbf{X}) = u_{in,i} - u_i(\mathbf{X})$
Niayifar and Porté-Agel (2016)	$u(\mathbf{X}) = u_\infty - \sum_{i=1}^{n} \Delta u_i(\mathbf{X})$, where $\Delta u_i(\mathbf{X}) = u_{in,i} - u_i(\mathbf{X})$

Simplified engineering approach

- Linear superposition of velocity deficit or energy deficit
- Different definitions of incoming flow, i.e. boundary layer flow, or inflow to that turbine

See also Zong, Porte-Agel, JFM 889, A8 (2020) for momentum deficit conservation

Stevens and Meneveau, Annu. Rev. Fluid Mech 49, 311-339 (2017)
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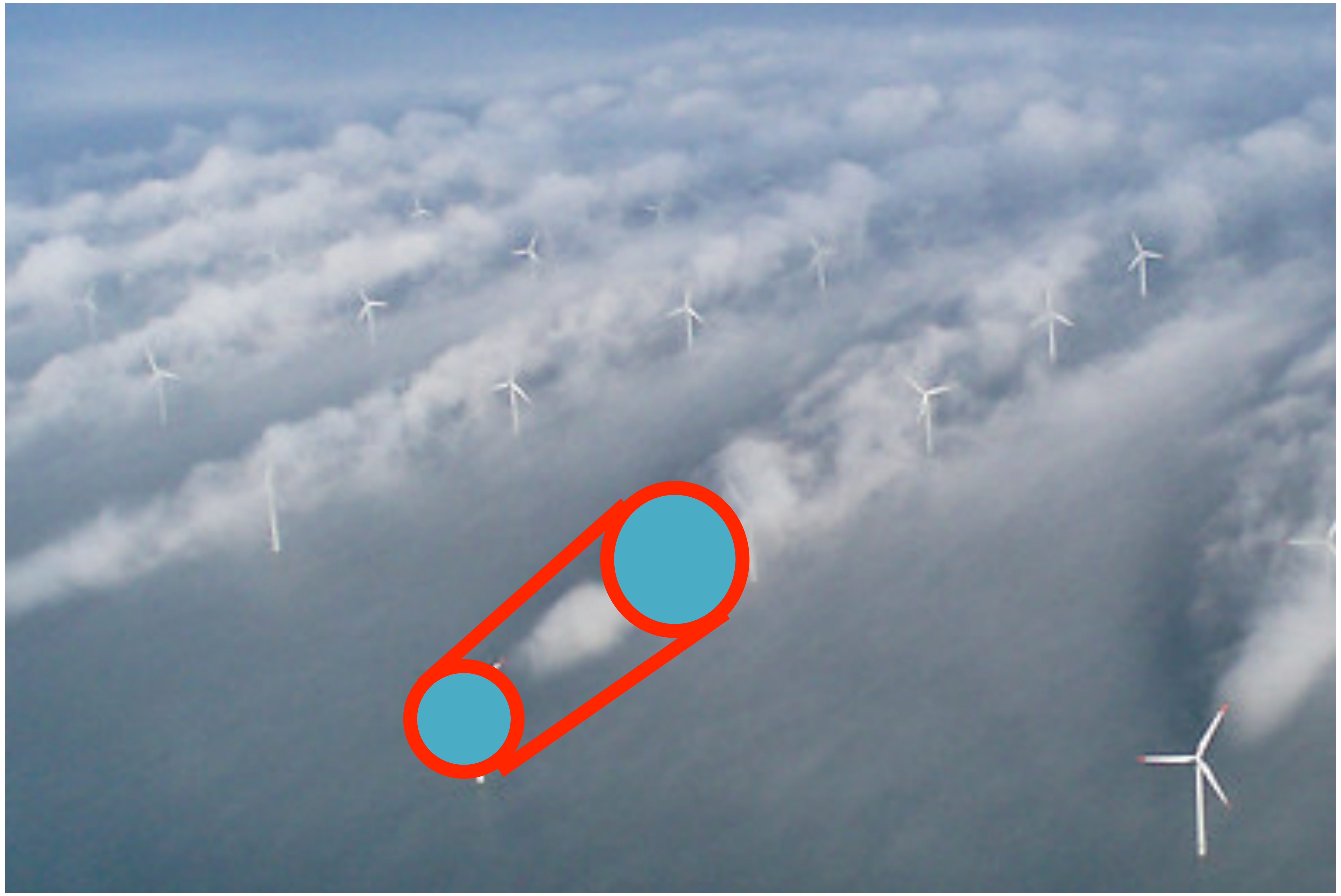
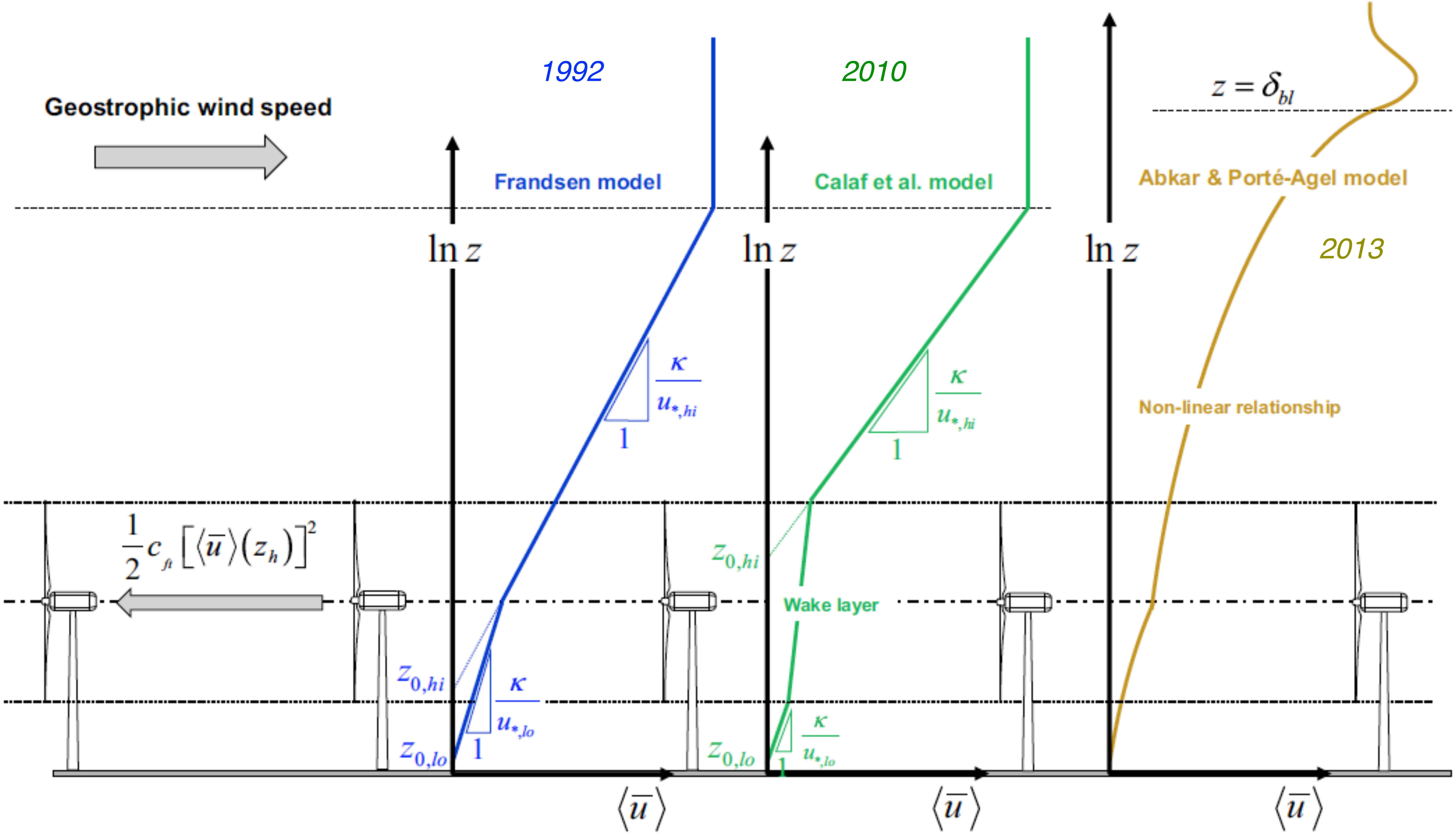
Wake effects in wind farms



Wake model **Top-down model**

Top-down model approaches



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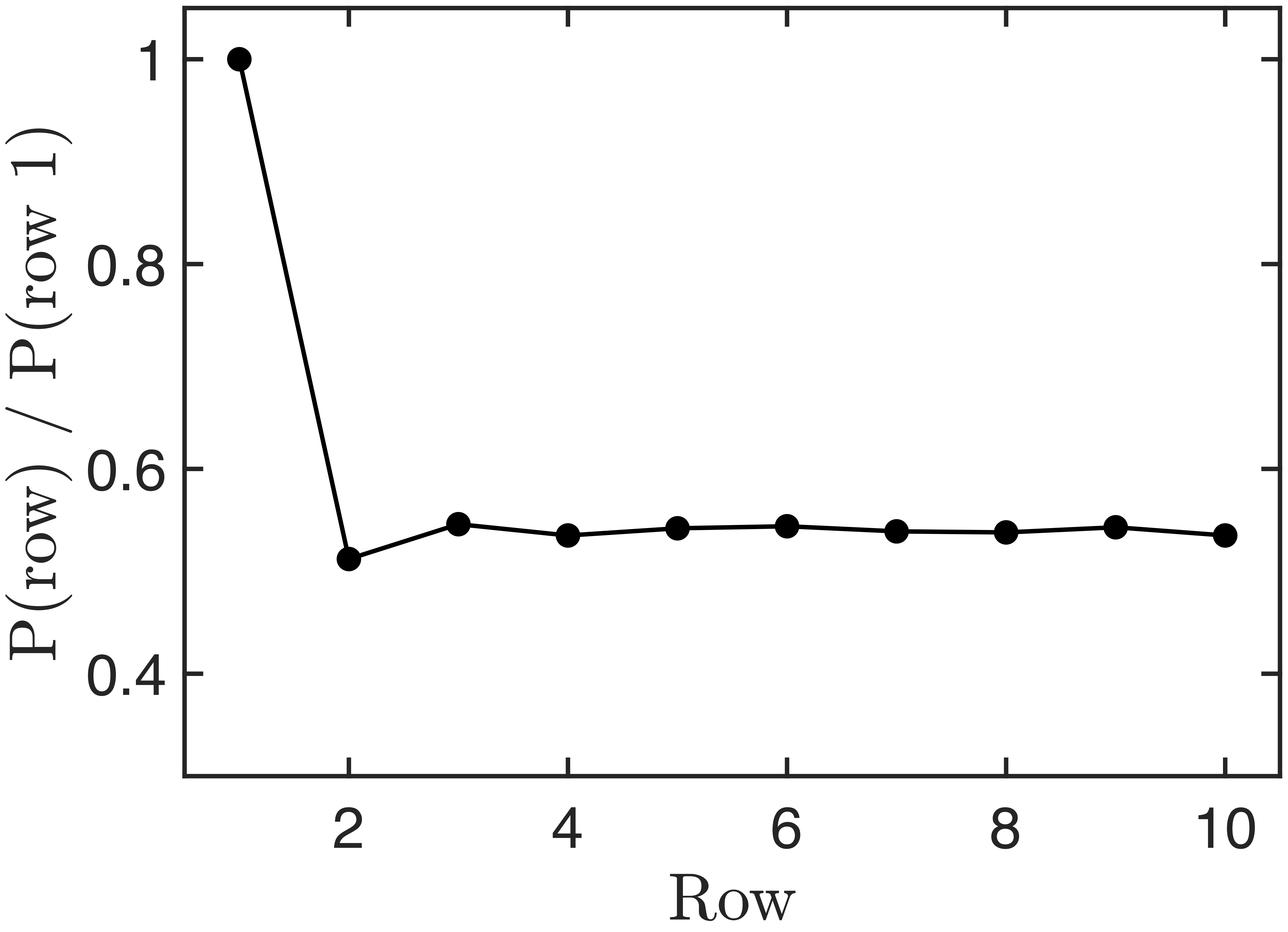
Comparison
analytical models to LES

Comparison analytical models with LES



LES

Stevens, Gayme, Meneveau, JRSE 7, 023115 (2015)
Stevens, Gayme, Meneveau, Wind Energy 19 (11), 2023-2040 (2016)

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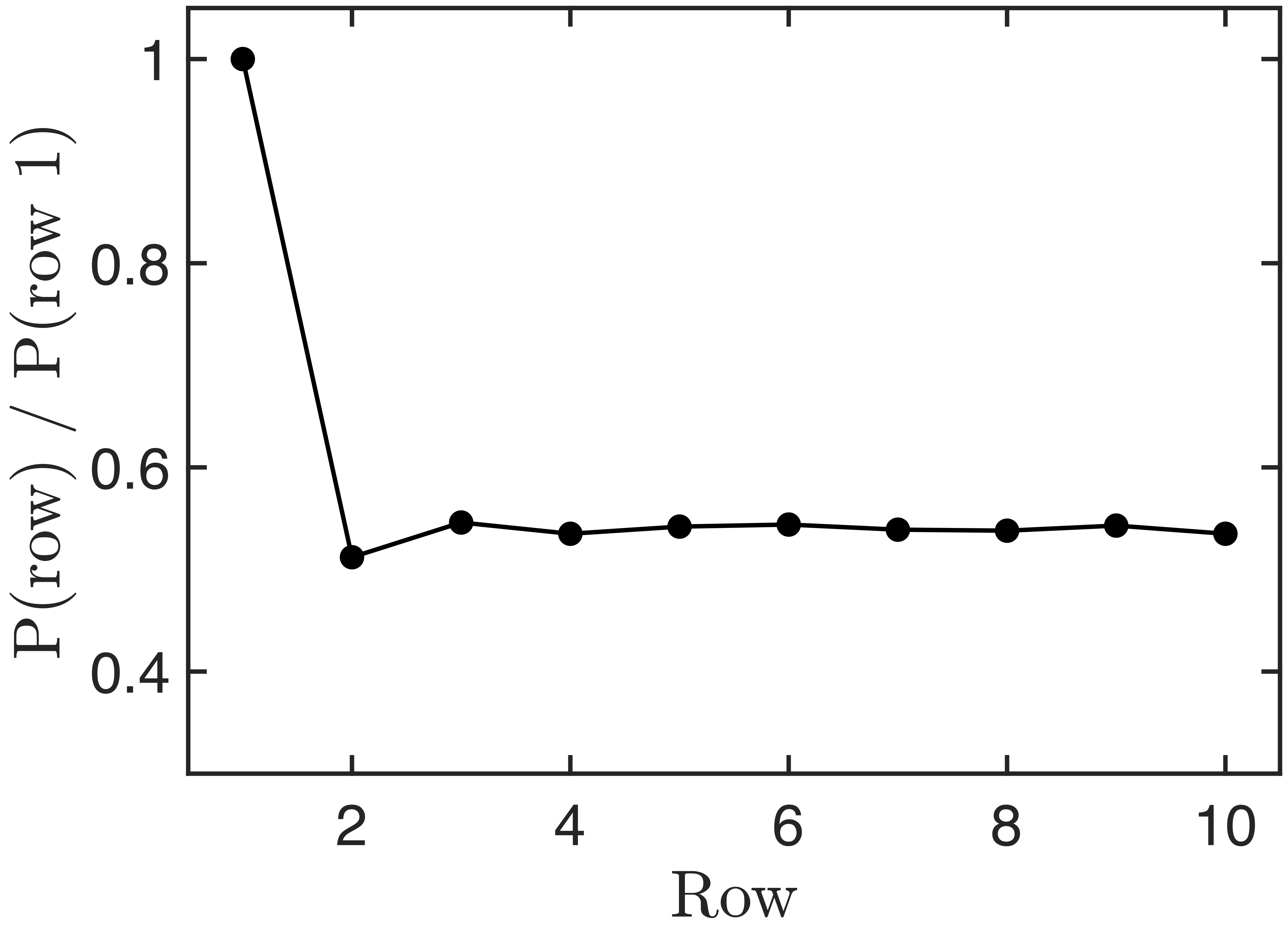

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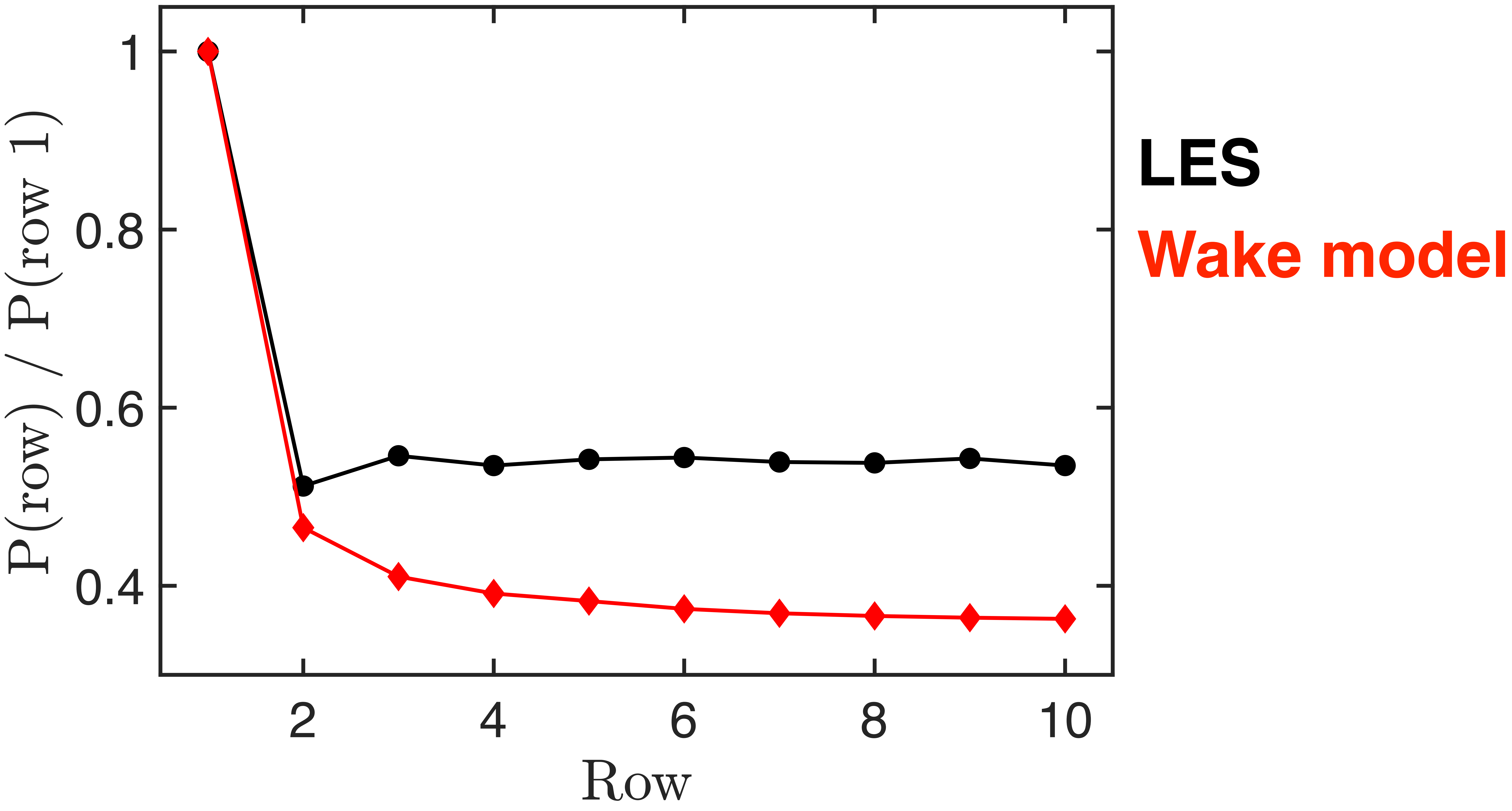

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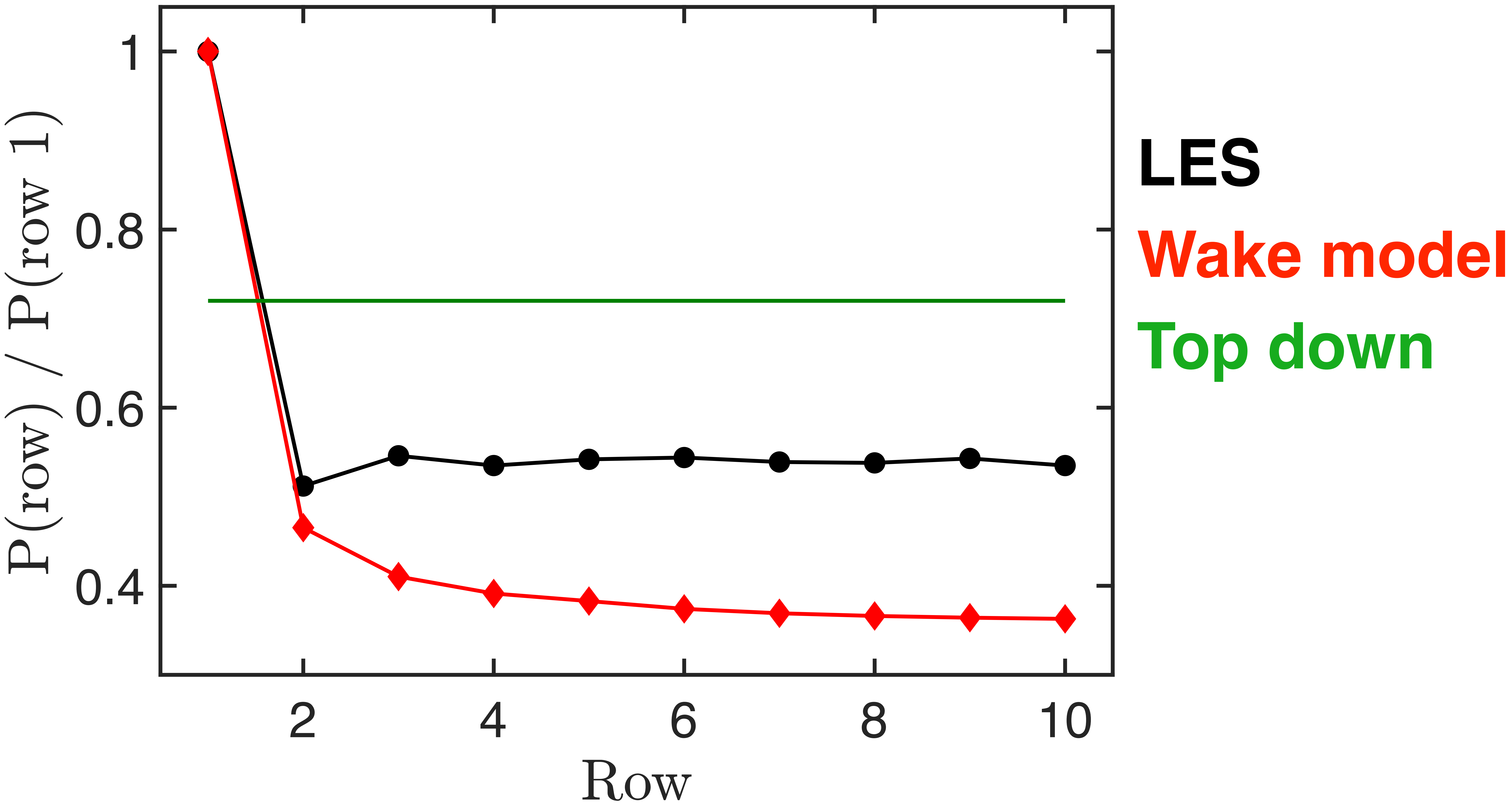

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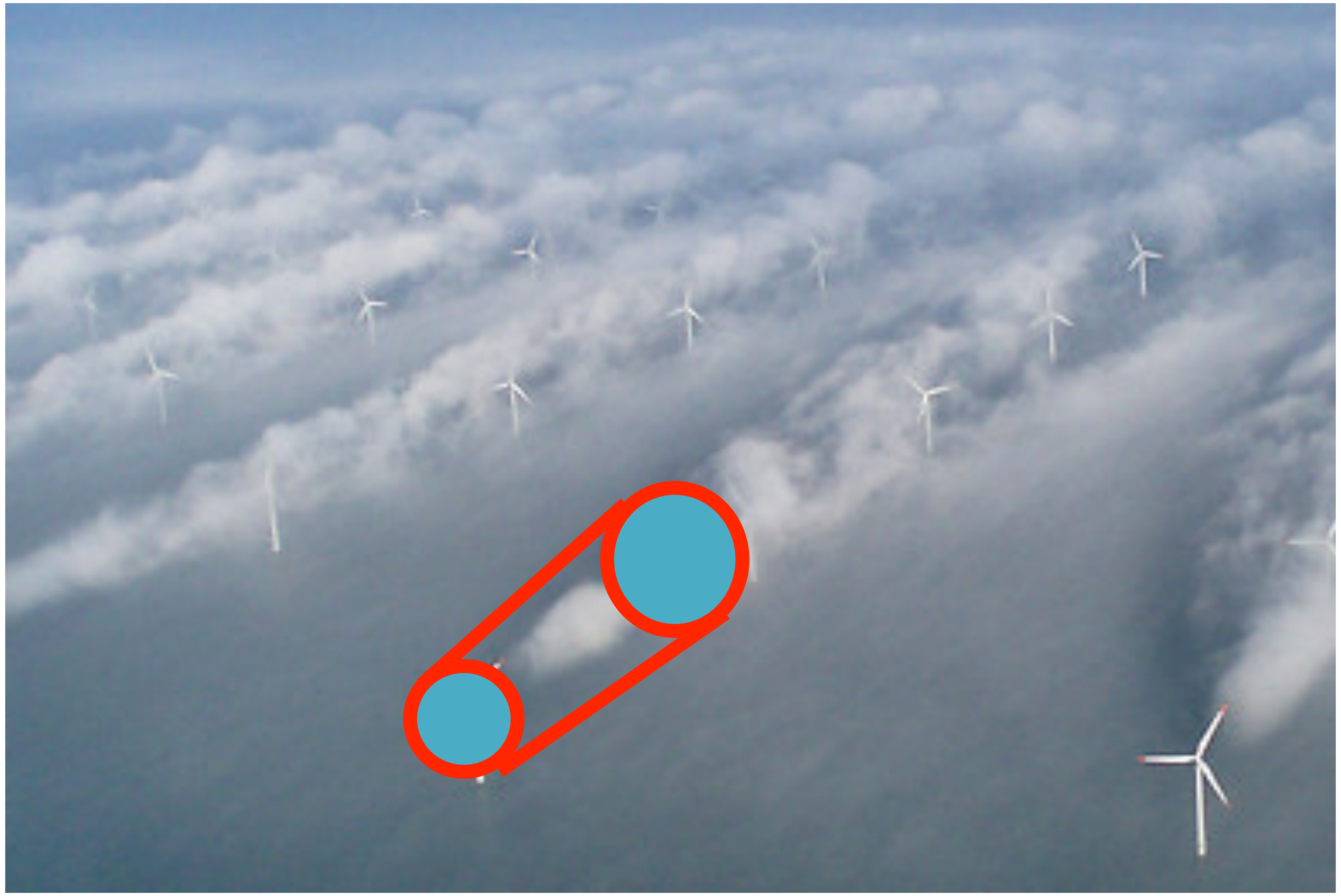
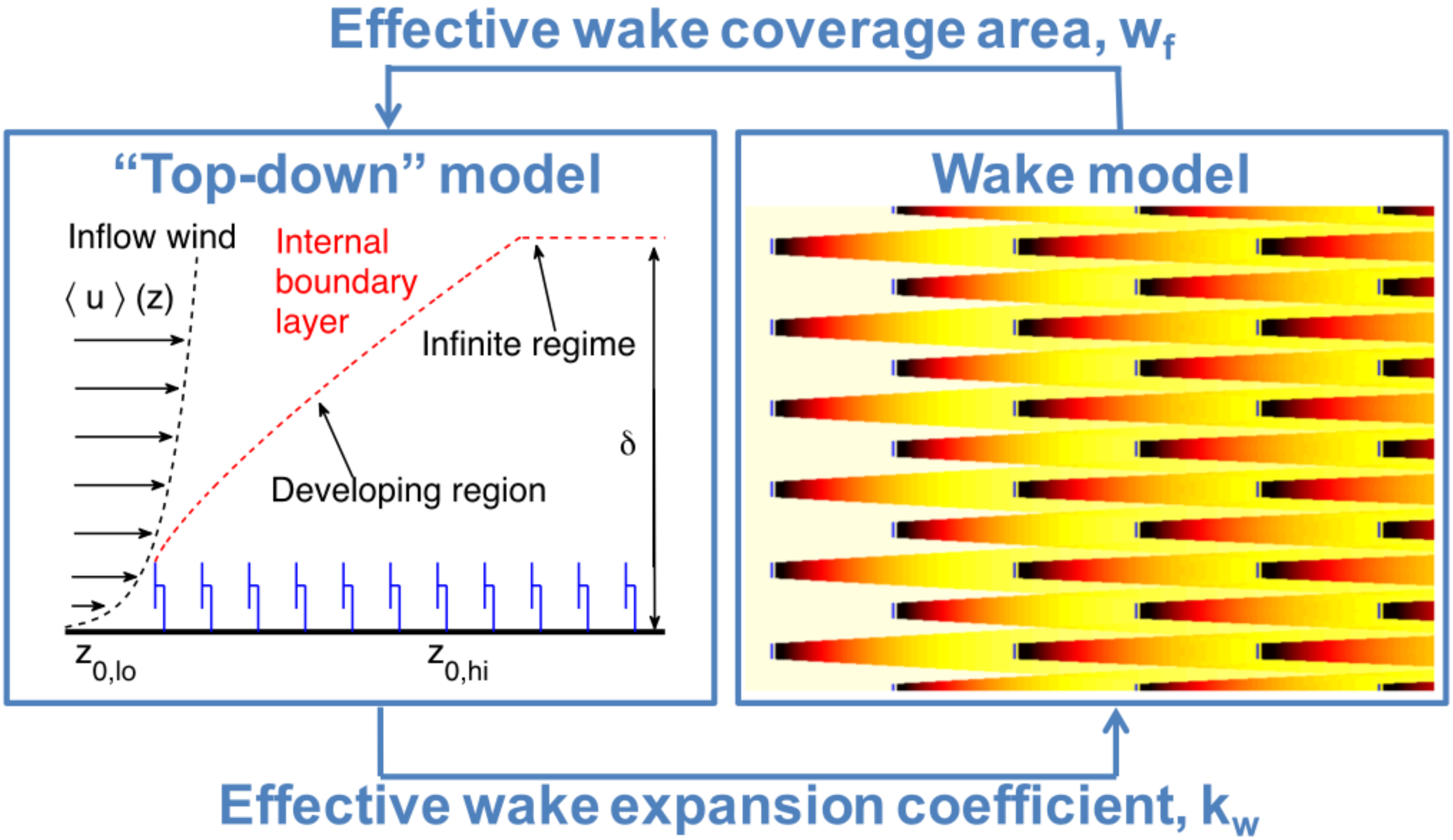
Wake effects in wind farms



Wake model

Top-down model

Coupled wake boundary layer model



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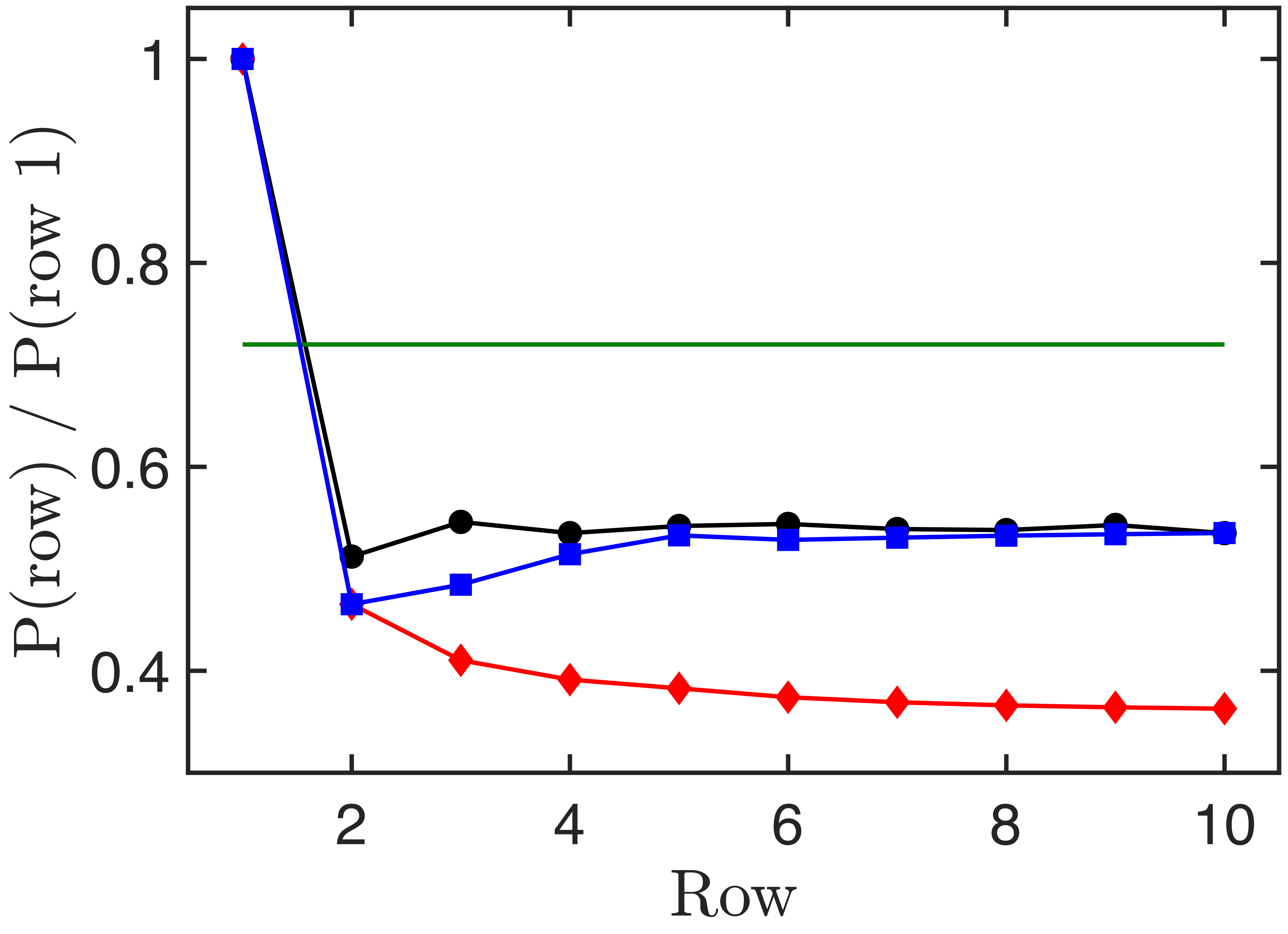


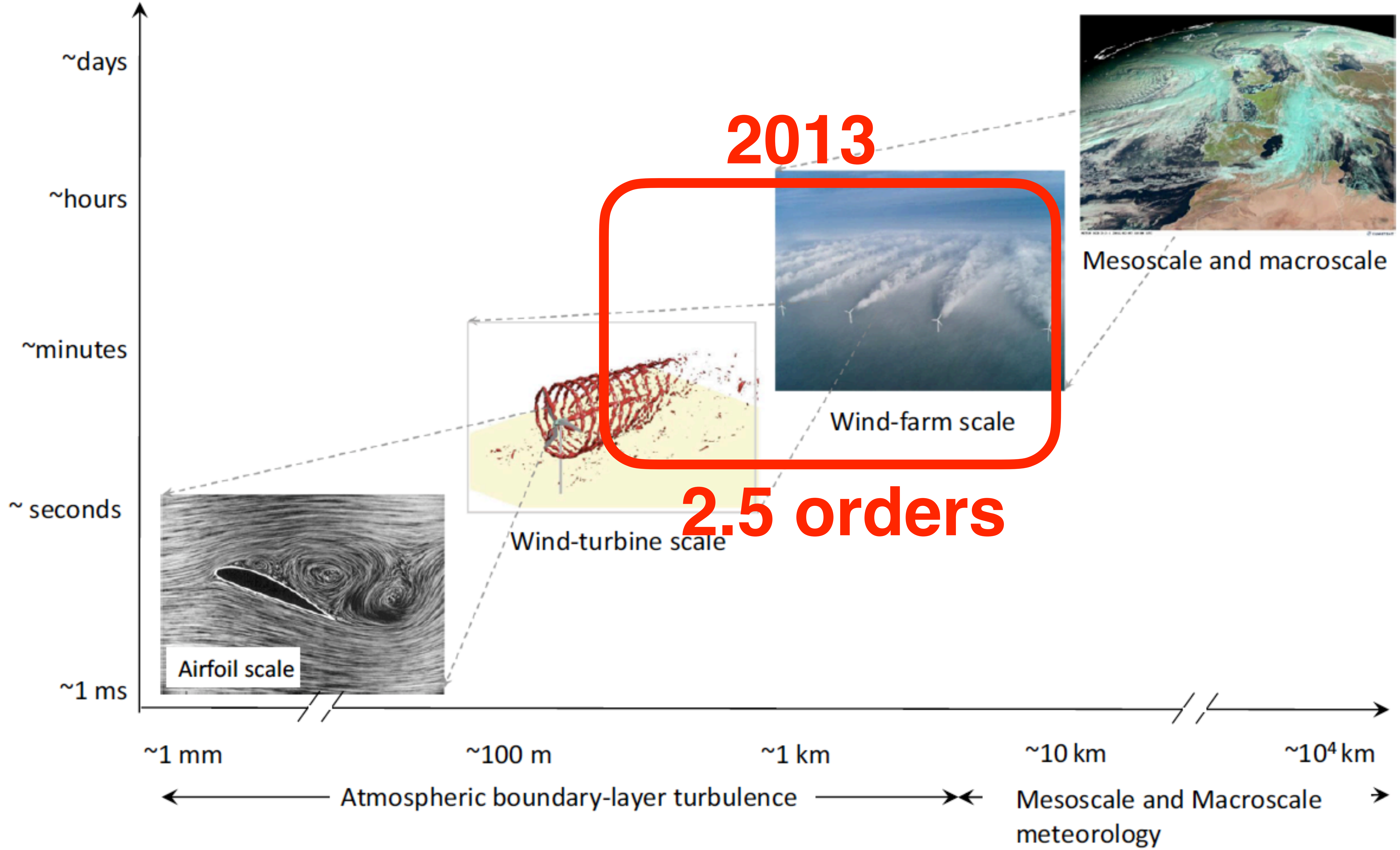
LES
Wake model
Top down
CWBL model

Stevens, Gayme, Meneveau, JRSE 7, 023115 (2015)
Stevens, Gayme, Meneveau, Wind Energy 19 (11), 2023-2040 (2016)

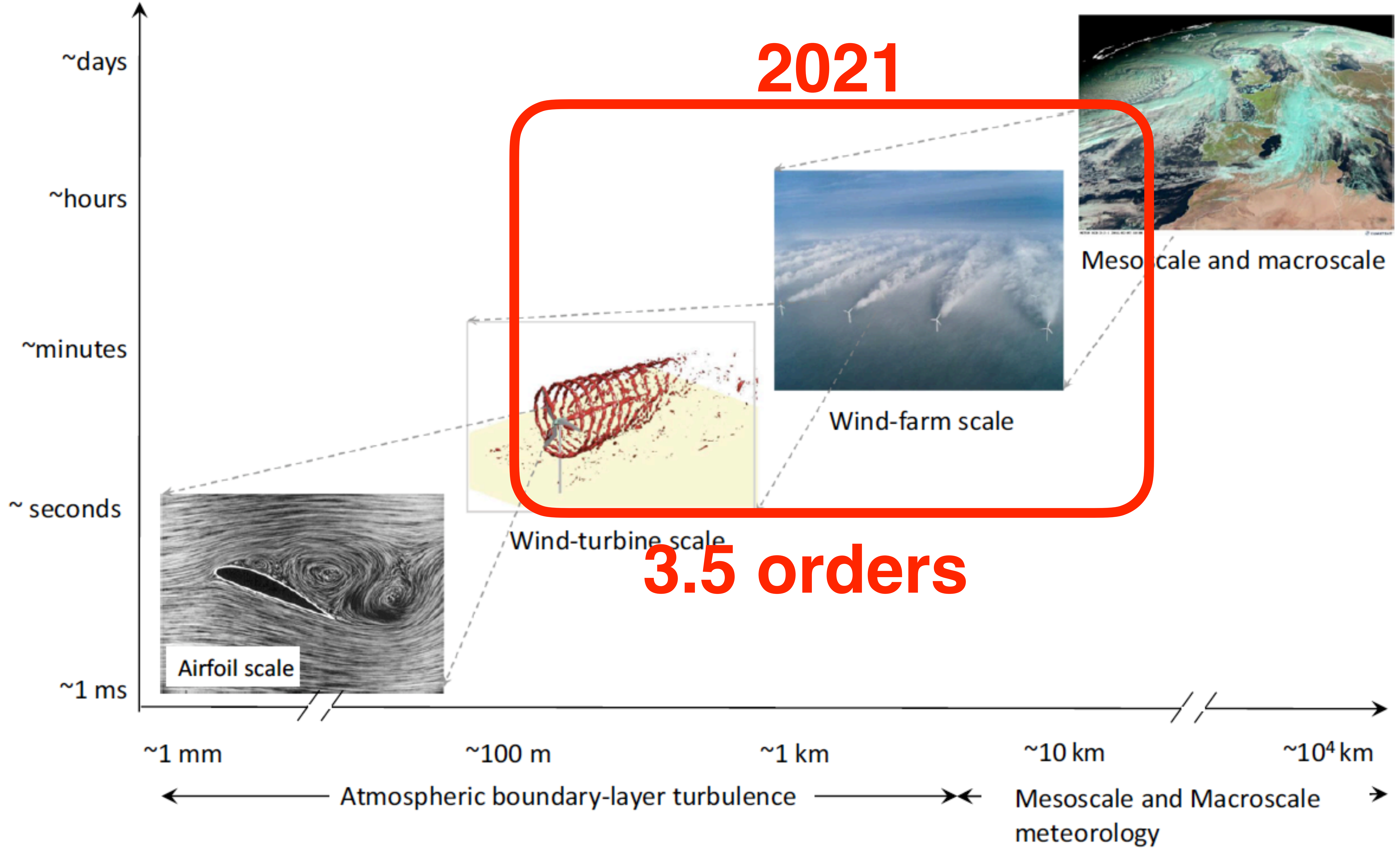
Comparison for the Horns Rev wind farm

Stevens and Meneveau, Annu. Rev. Fluid Mech 49, 311-339 (2017)

High performance wind farm simulations

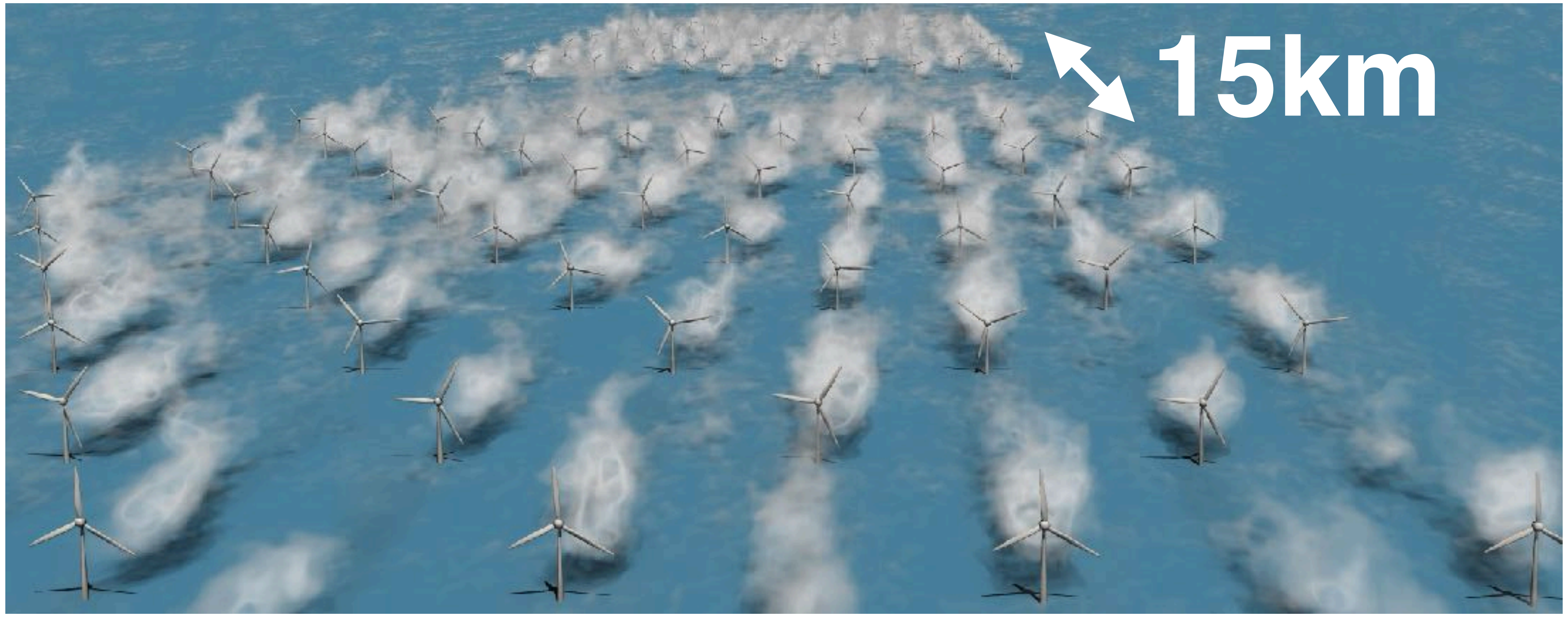


High performance wind farm simulations

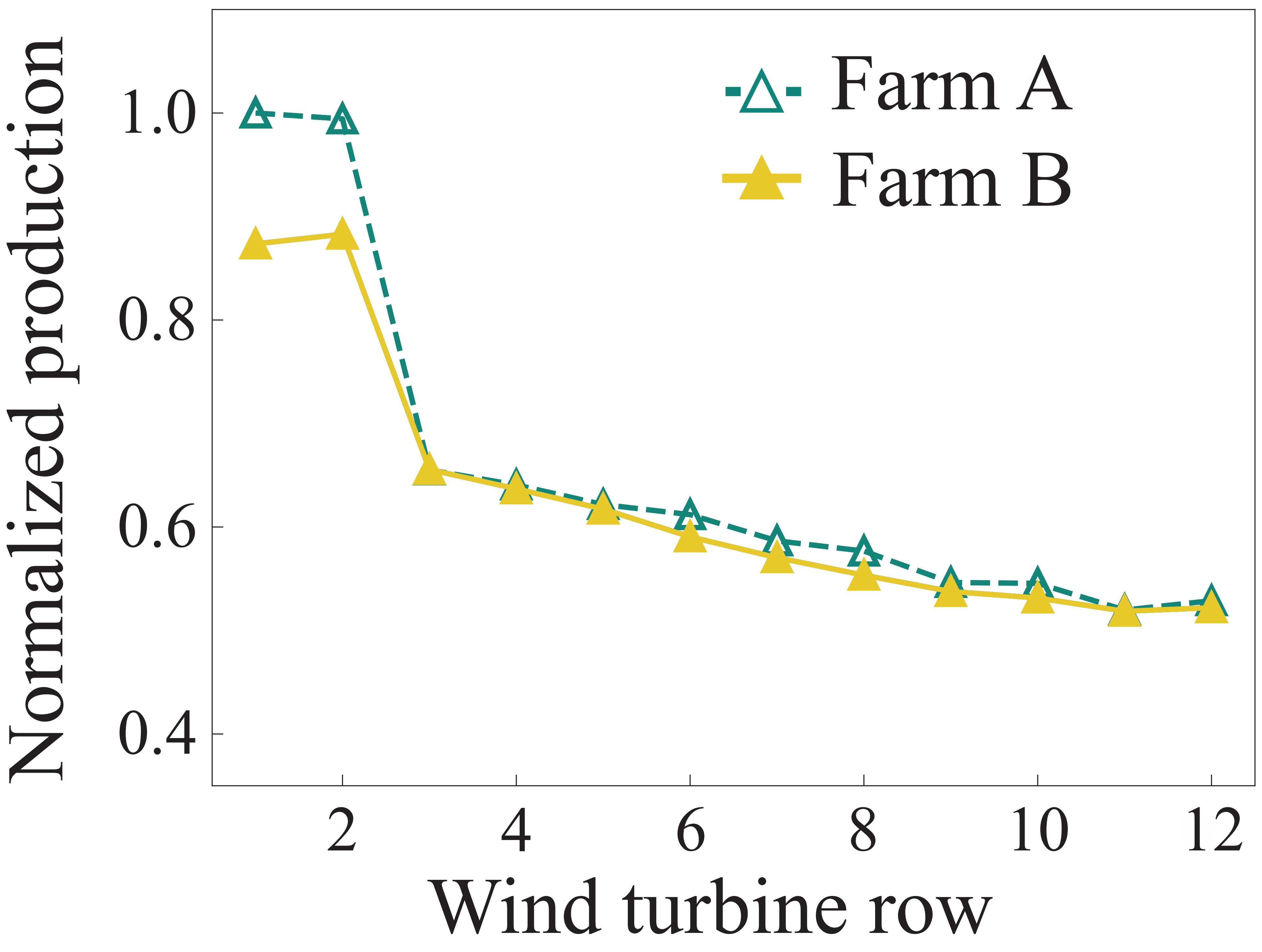


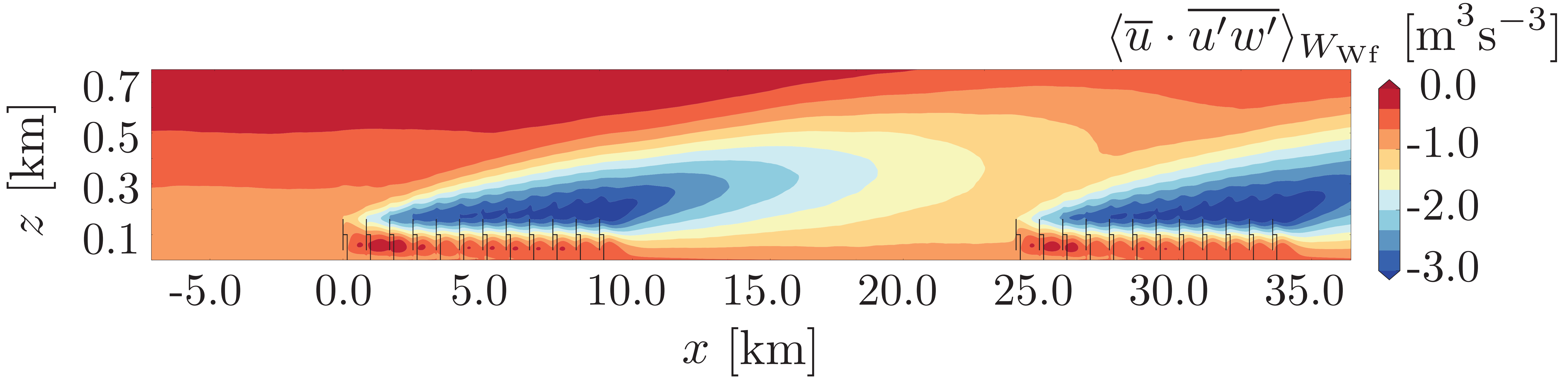
Interaction between wind farms

Farm B



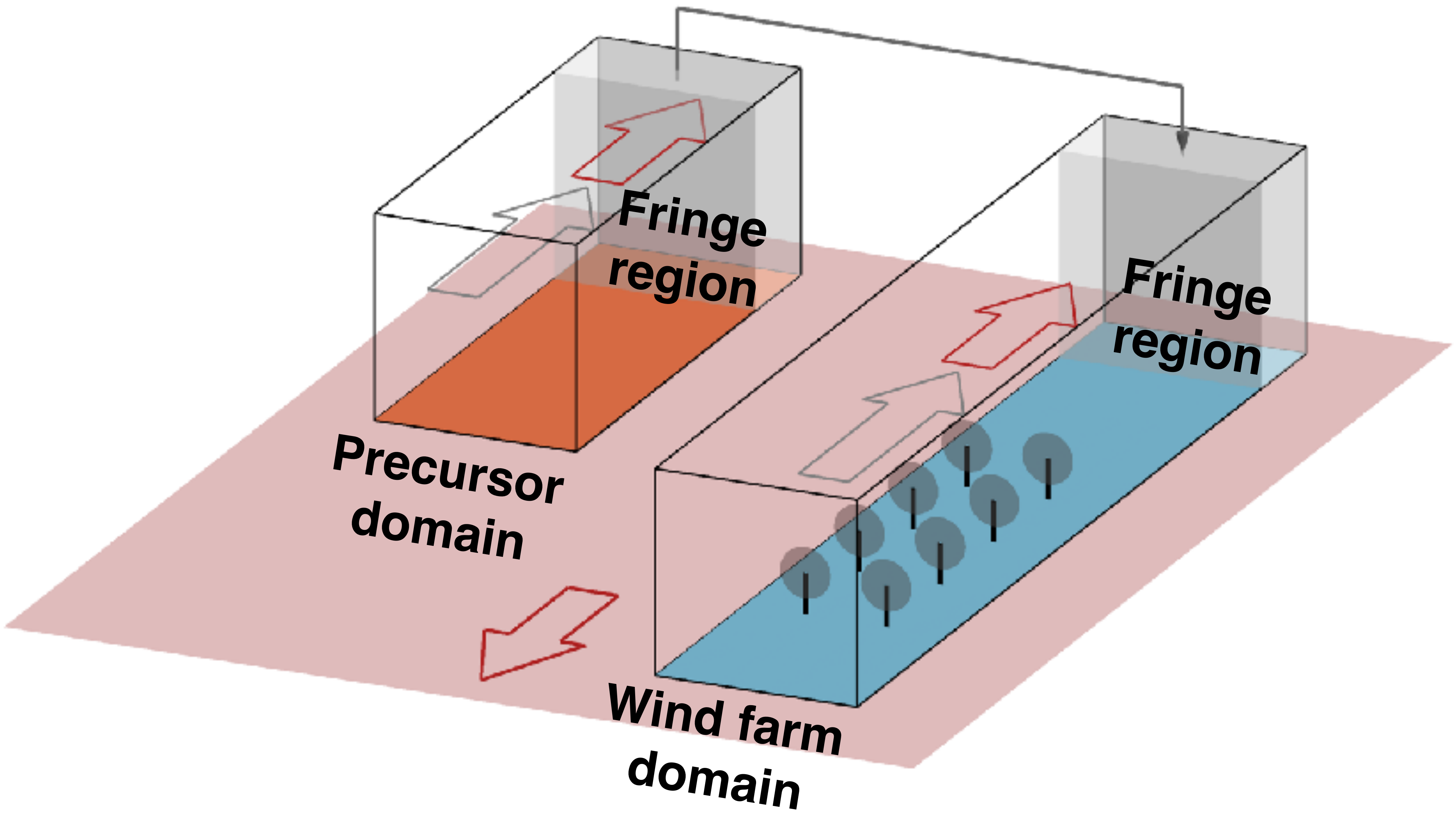
Farm A

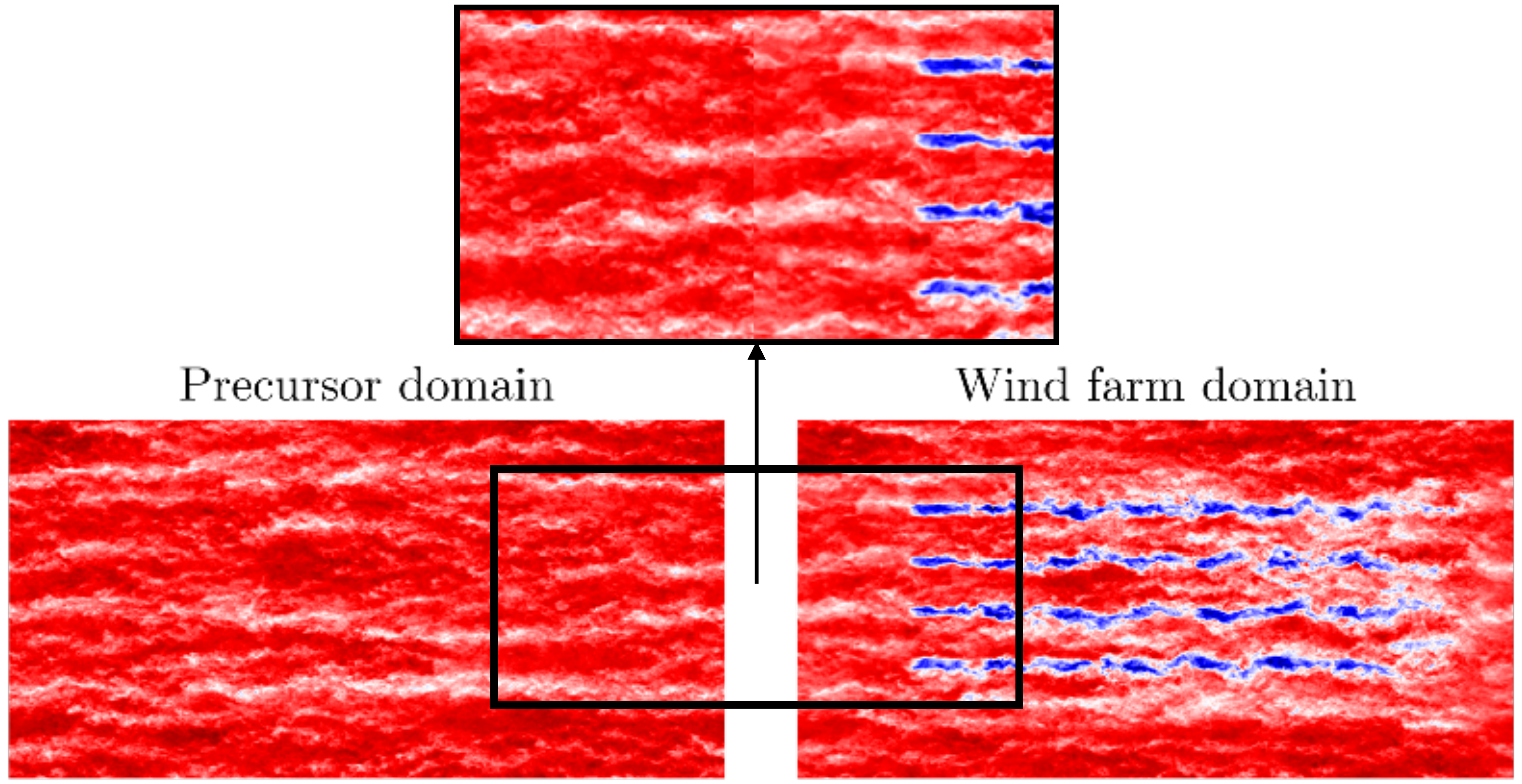


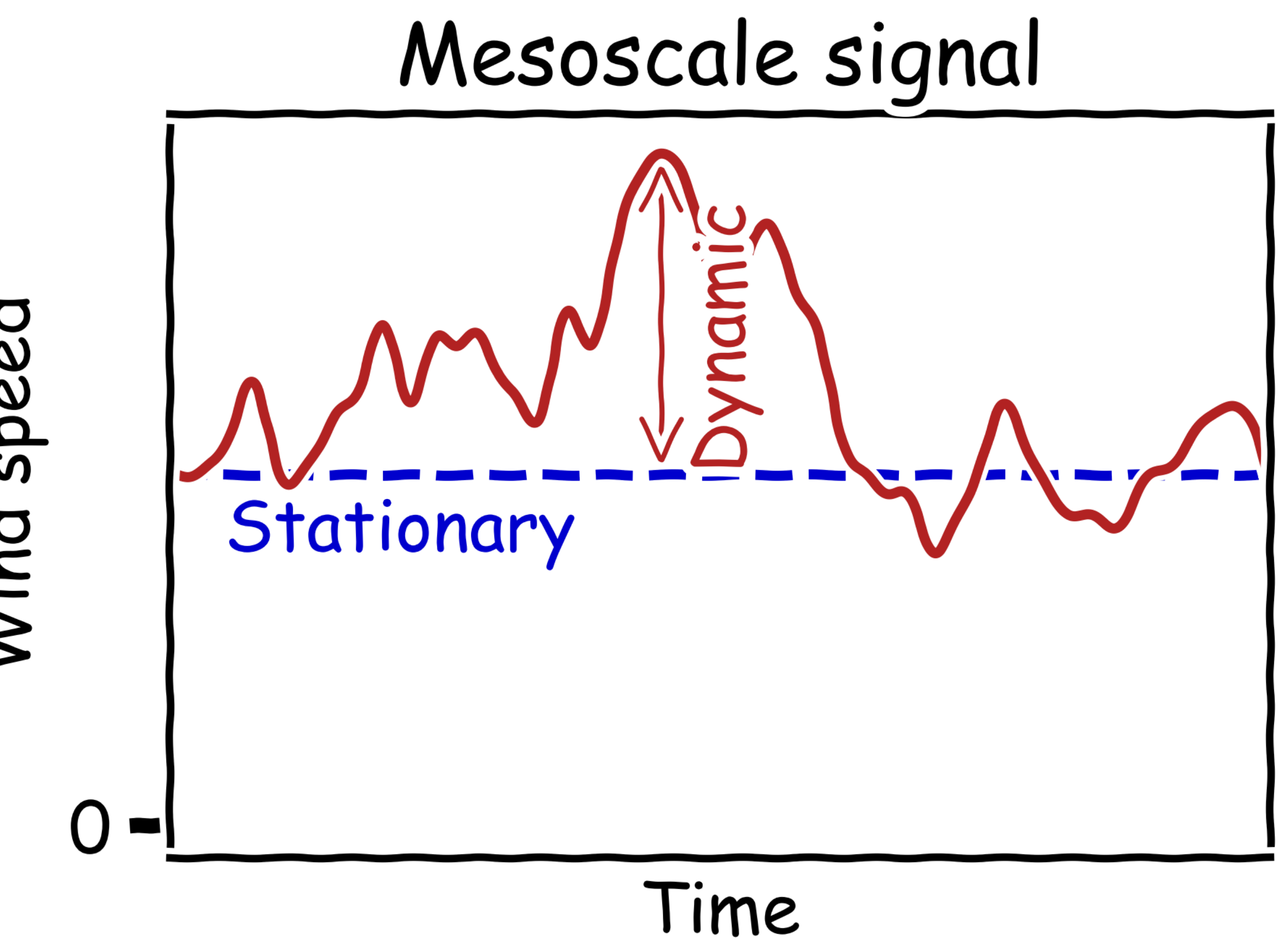


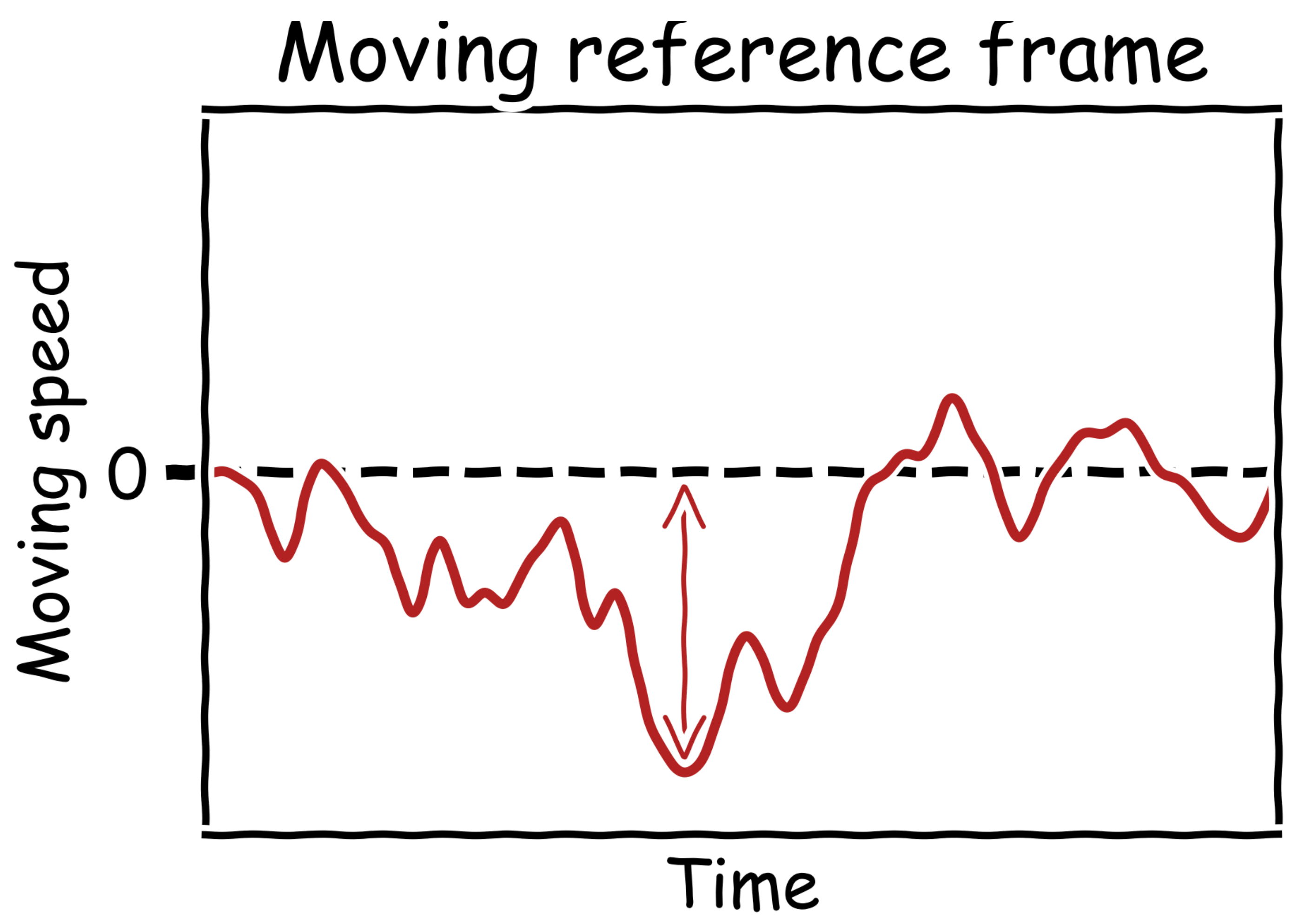
Stieren, Stevens, Flow 2 E21 (2022

Unique concurrent precursor approach





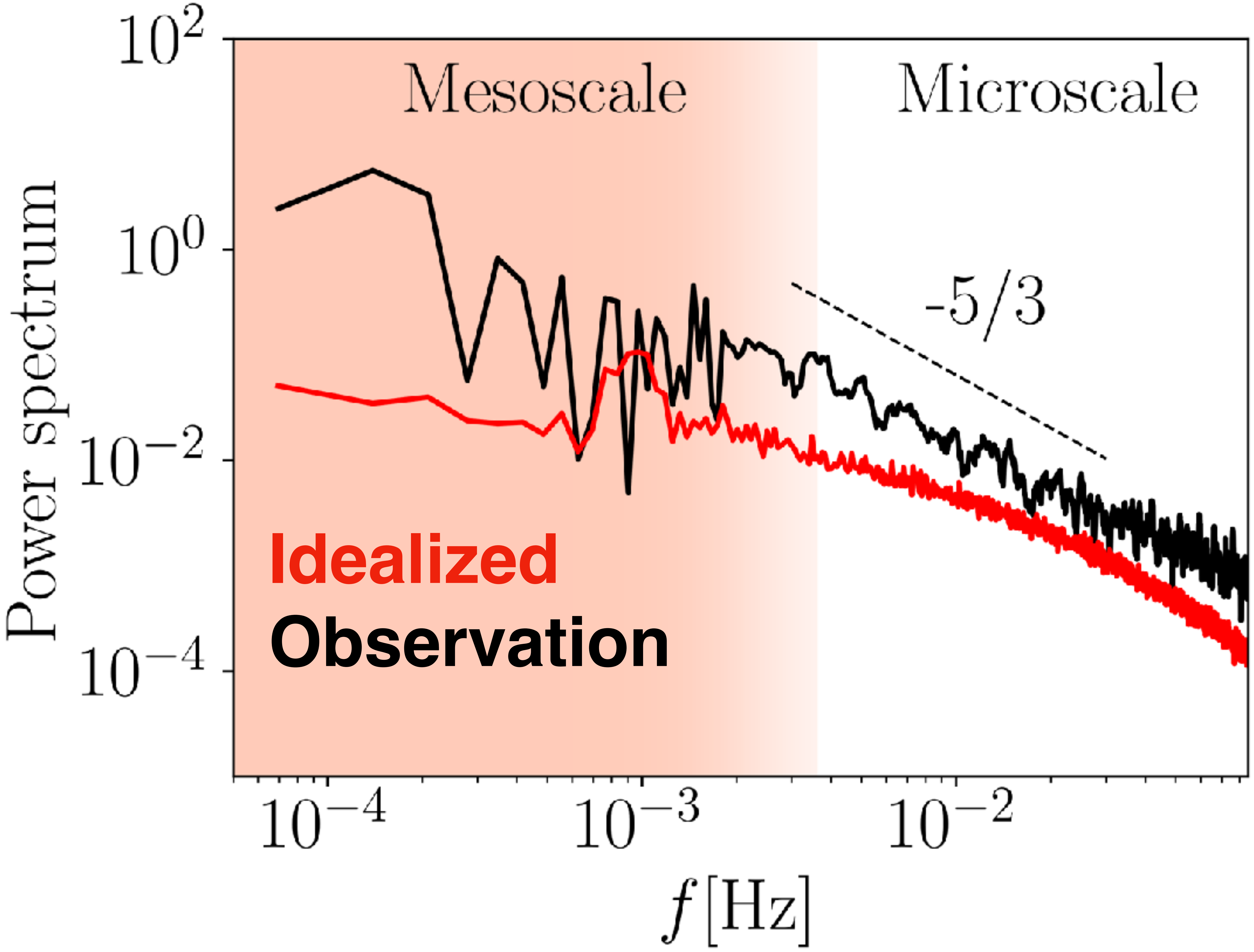




$$\partial_i \tilde{u}_i = 0$$

$$\partial_t \tilde{u}_i + \partial_j(\tilde{u}_i \tilde{u}_j) = -\partial_i \tilde{p}^* - \partial_j \tau_{ij} - \frac{\partial_i p_\infty}{\rho} + \mathrm{d}_t U \delta_{i,1}$$

Dynamic wind conditions



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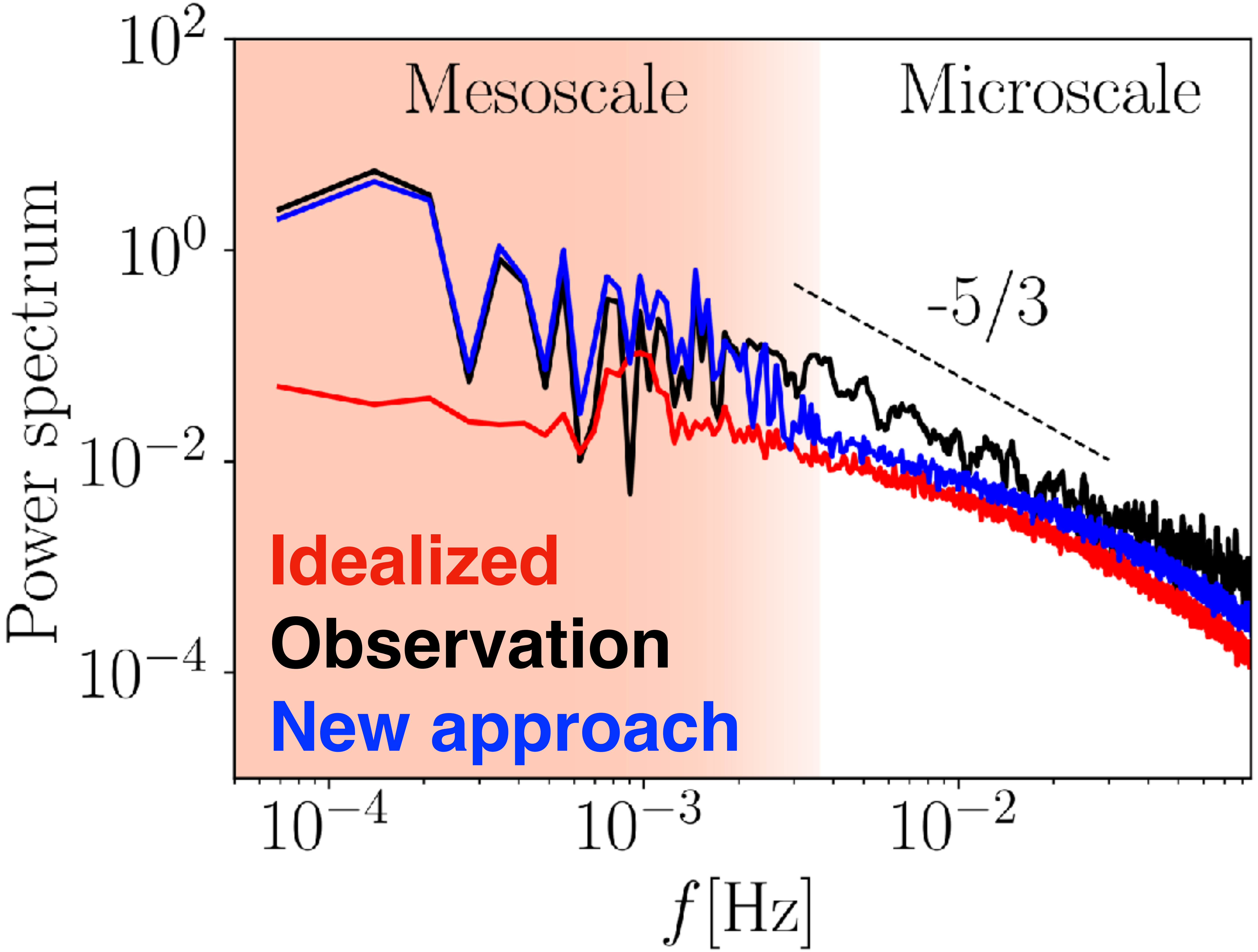
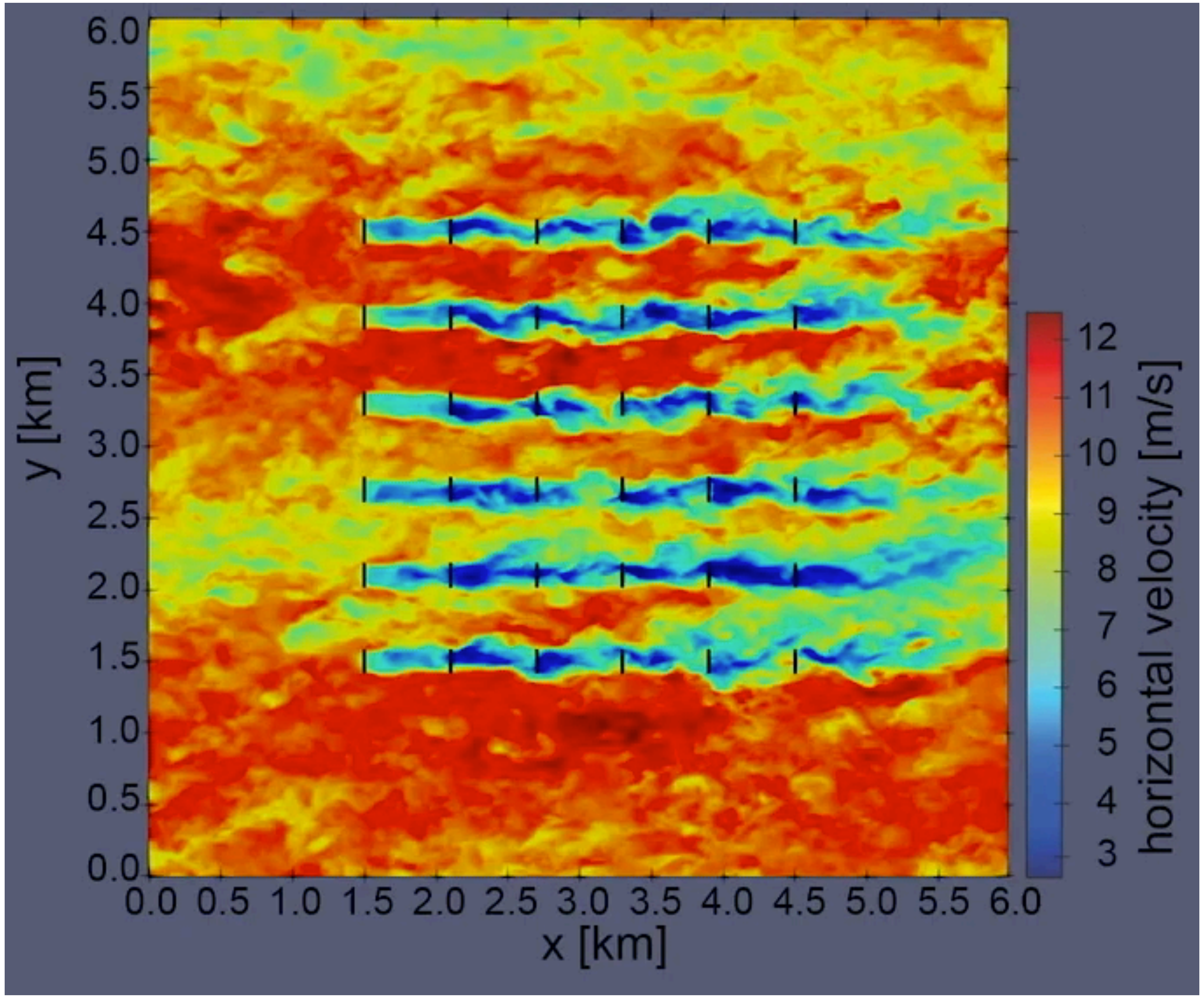
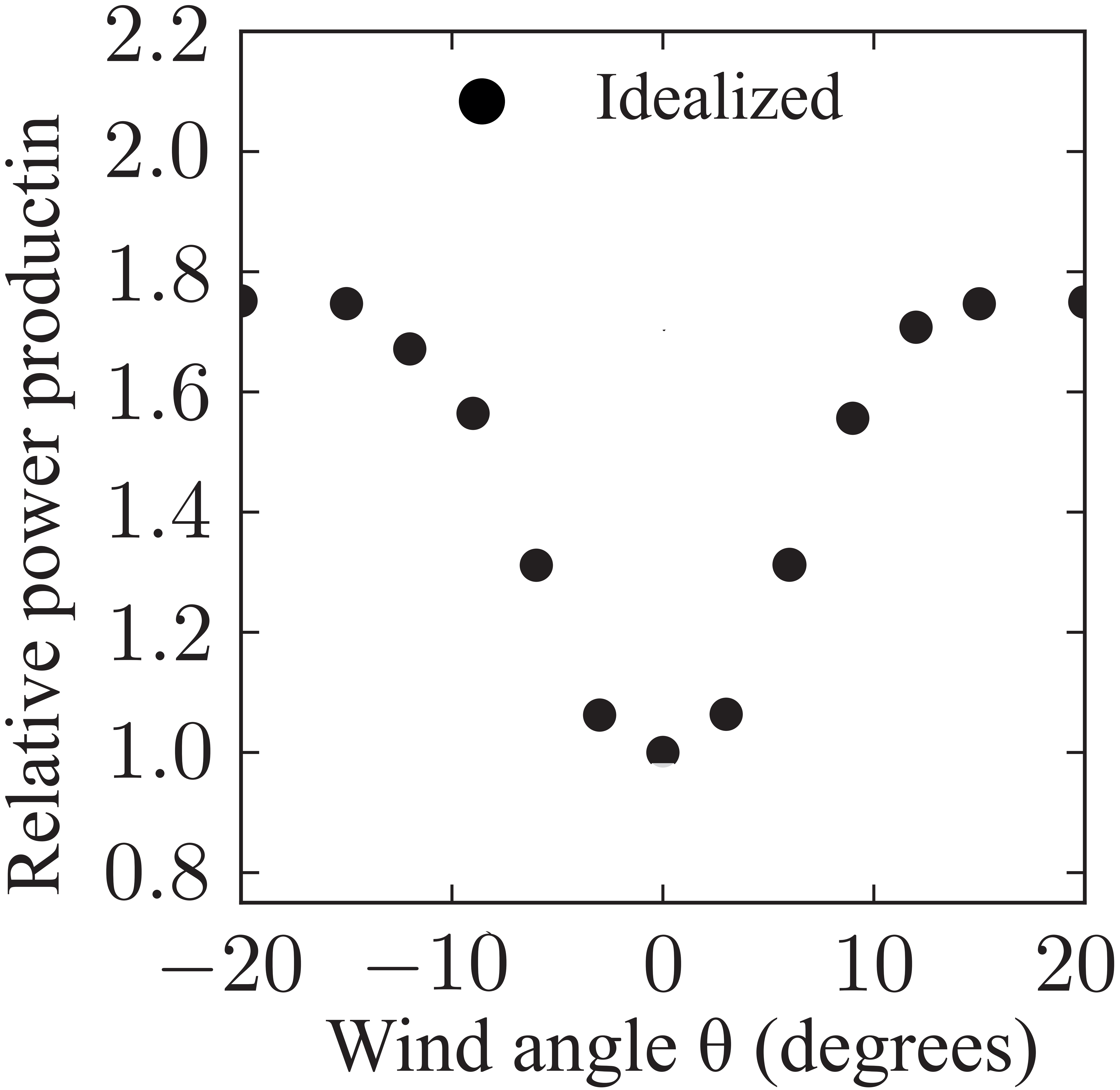
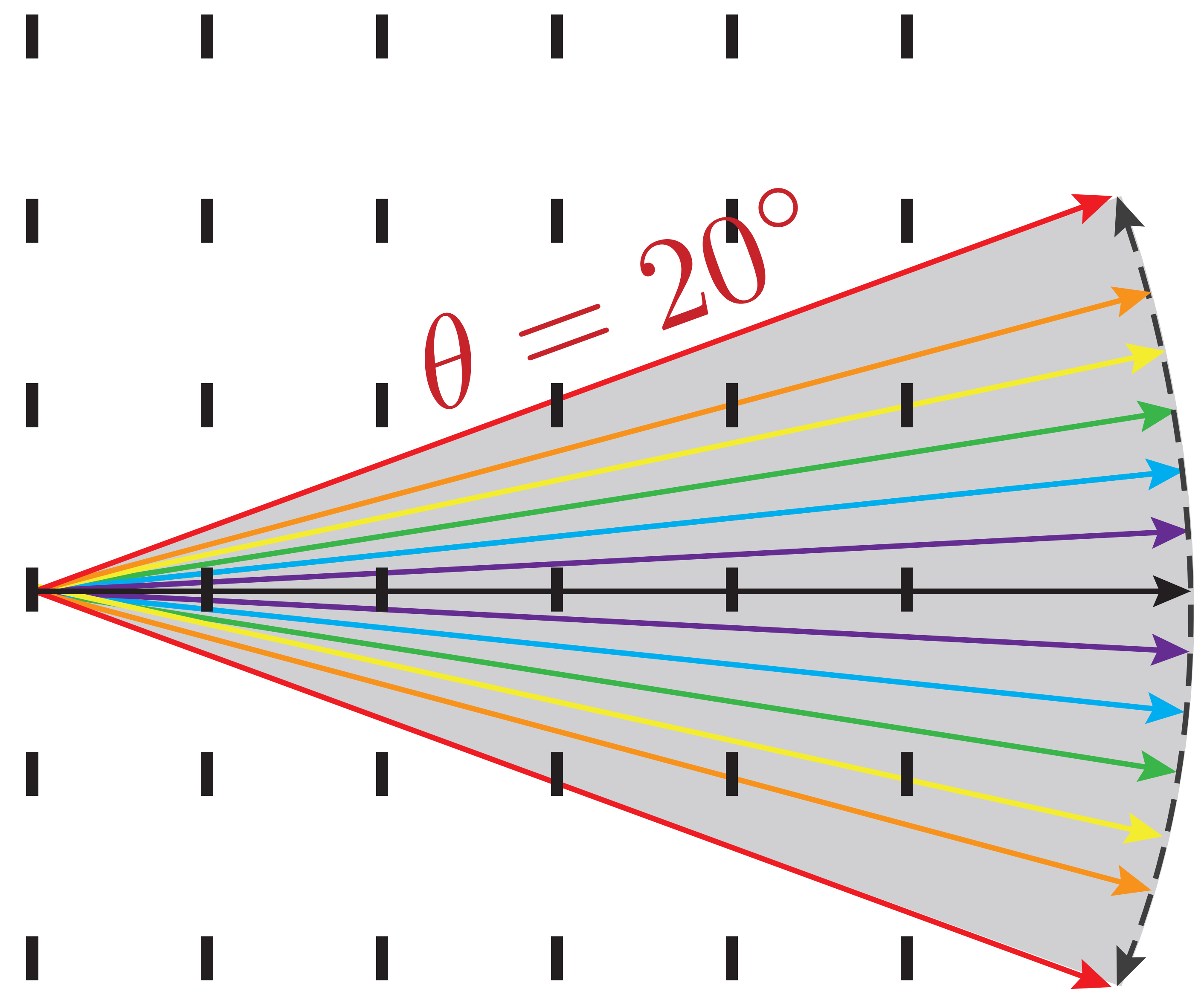


Dynamic wind direction changes



Impact dynamic wind direction changes





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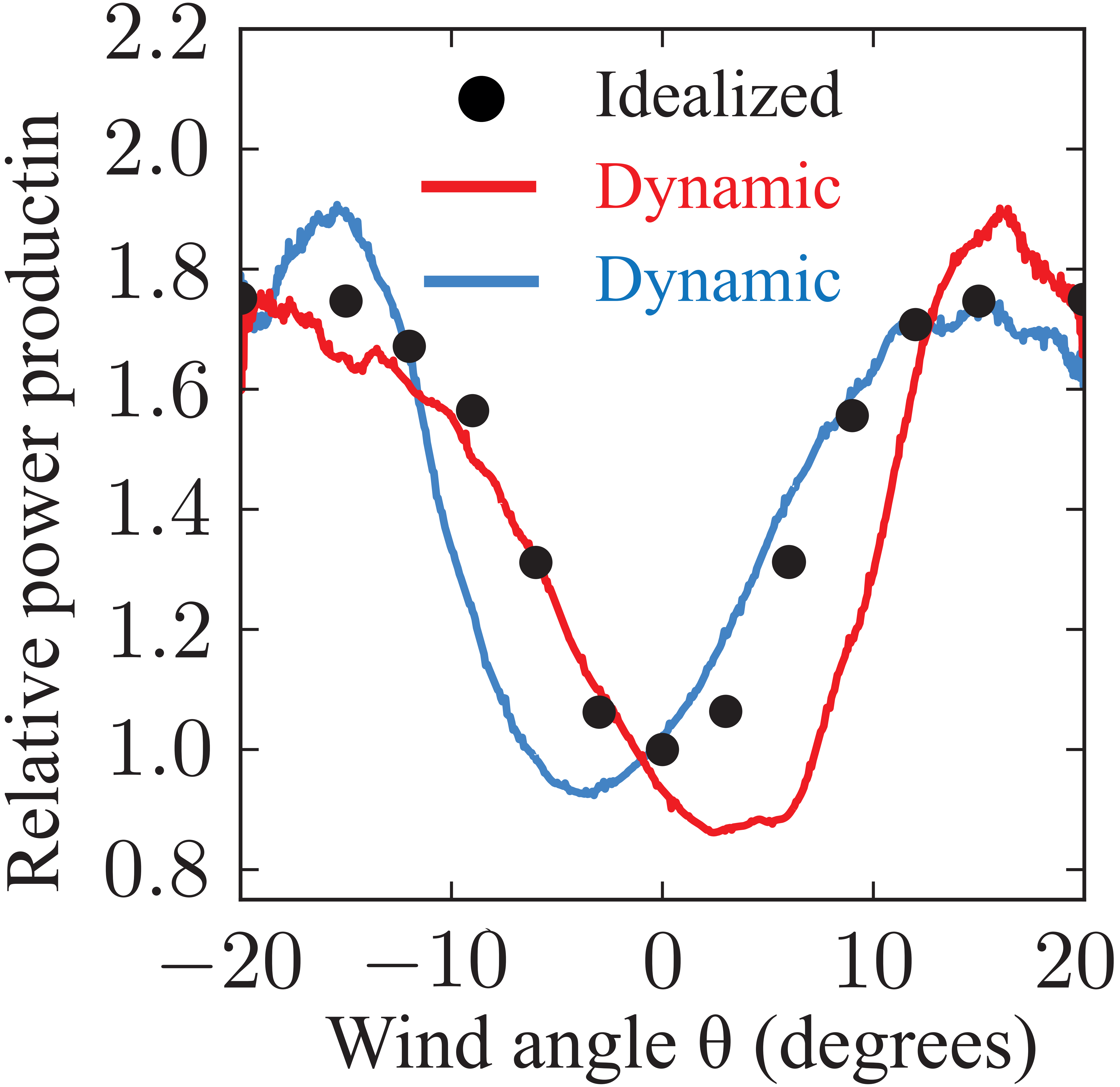

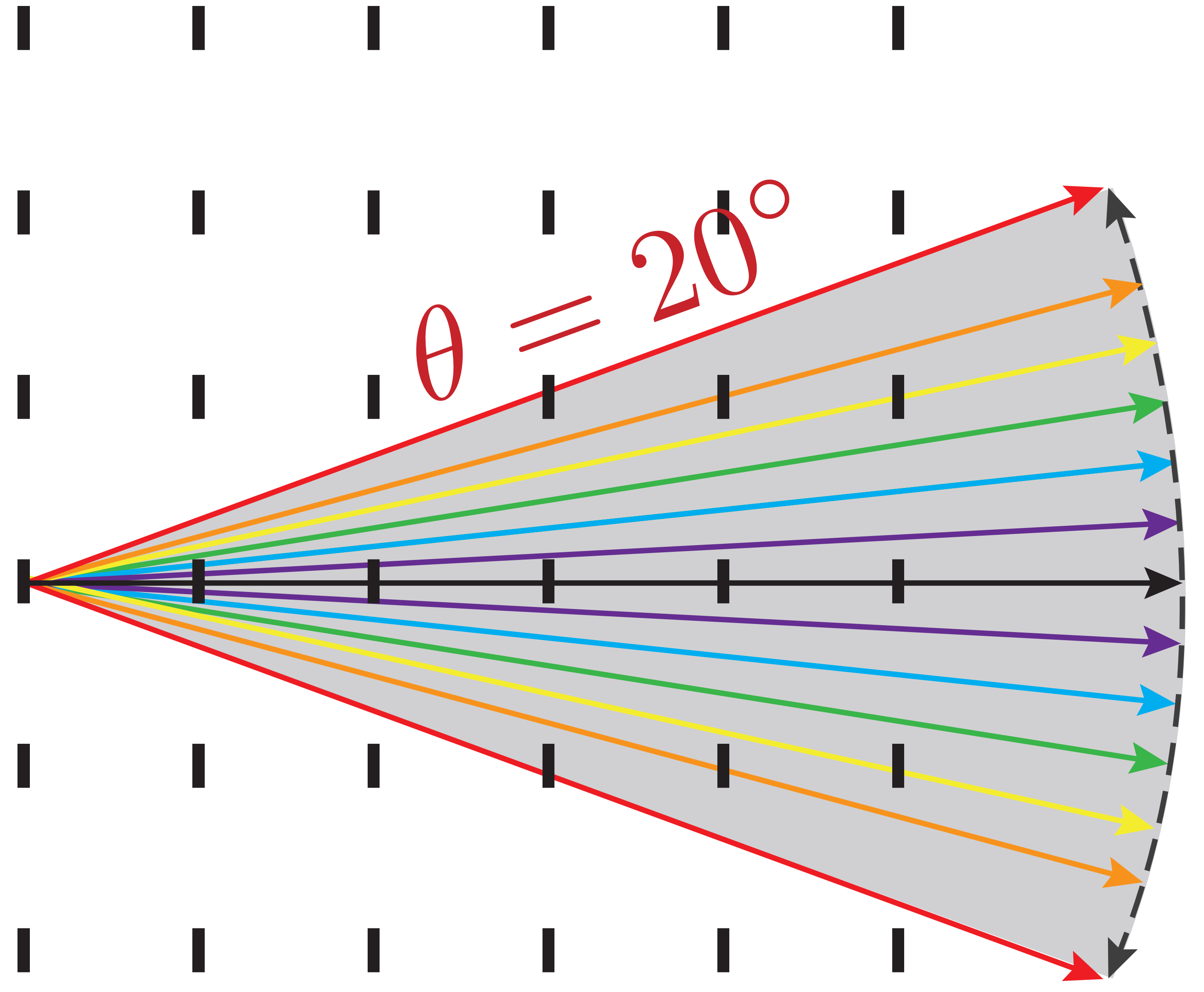

Thanks for your attention!

Questions?